проводилась на основі розв'язання спряженої задачі Стефана, яка складалась із рівняння теплопровідності для ТАМу та рівняння конвективного теплообміну для теплоносія системи перетворення. Ці рівняння доповнювались відповідними граничними та початковими умовами. На границі розподілу фаз в ТАМі, де функція температури має розрив, проводилось згладжування параметрів за методом «Mushy layer» [3]. Вільна конвекції, що виникає в розплаві ТАМу враховувалась квазістаціонарним методом з використанням критеріальних рівнянь. Розроблену математичну модель було розв'язано методом контрольного об'єму за допомогою створеного Python-коду. В якості фізичної моделі розглядалась система типу «труба в трубі», де ТАМ розташовувався в кільцевому просторі між стінкою каналу з теплоносієм та зовнішньою границею. Моделювання проводилось із нітритом натрію $NaNO_3$, температура та теплота фазового переходу якого складає $T_ф$=306^{0}С та 172 кДж/кг, відповідно. В результаті числового моделювання отримані поля температур та відповідних теплових потоків в теплоносії, в рідкій та твердій фазі ТАМу, знайдено закон руху границі розподілу фаз на режимі розрядки та зарядки, його залежність від початкової температури та швидкості теплоносія, час повної зарядки та розрядки теплового акумулюючого модуля.

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ENERGY STORAGE WITH INTEGRATED THERMAL FIELD EMISSION CONVERSION AND INSULATION

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Thermal energy storage (TES) supported concentrating solar power (CSP) systems with 3D-printed photon-enhanced thermal field emission (PETFE) converters and plastic reflectors could dramatically lower the cost and energy payback time of the CSP technologies. The PETFE panels with a transparent anode, carbon nano-tube (CNT) ink printed on a dielectric substrate as a cathode surrounded on both sides by a gate can be used for direct on-sun heating and thermal insulation of the TES during off-sun hours. An additional PETFE converter design could have a thin anode containing a large number of cooling micro-channels to serve as the CSP receiver. CO2 gas from the PETFE anode at the temperatures of about 650°C heats sCO2 Brayton and/or steam Rankine cycles.

Introduction

Presently, solar energy is harnessed by either using photovoltaic (PV) panels or solar thermal collectors. Multiple bandgap PV cells allow reducing the relaxation energy loss and substantially increase the power-conversion efficiency. The choice of materials for each sub-cell is very limited due to the difficulties in extracting the current between the layers caused by the requirements for lattice- and current-matching.

One limitation of the traditional CSP compared to PV panels is that CSP cannot generate electricity during cloudy periods, when diurnal light intensity (DNI) is below a lower threshold around 400 W/m2. The minimum required DNI above which power generation of the TES-enhanced CSP would become feasible is around 200 W/m2. In the novel thermal energy storage systems, a hot tank with low-cost silica sand or phase change materials (PCM) can be surrounded by the photon-enhanced thermal field emission conversion and insulation panels.

The design concept with a transparent anode, front side illuminated photocathode and gate utilizes the transition region between field emission and thermionic emission known as photon-enhanced thermal-field emission (PETFE). A projection lithography or 3D-printed PETFE panel design with a transparent anode is similar to field-effect PV concept and used to thermally insulate the TES. A second PETFE panel design that similar to photon-enhanced thermionic emission (PETE) concept serves as a CSP receiver. The window should be stable at the high temperature of the cathode, leading to the selection of materials such as quartz or sapphire. The cathode and anode separation by a vacuum gap forms the plate capacitor. In the transmission TFE at some conditions, the energy cathode-to-anode transition can be close to 1.

The both designs could have a gate made of high dielectric constant and negative electron affinity (NEA) materials and a photocathode. For example, ferroelectric materials are typically highly insulating because of large band gaps, which limits the absorption especially of visible light. A traditional photon-enhanced thermionic emission (PETE) converter has a p-doped narrow-bandgap semiconductor cathode separated by a vacuum gap from a PCM or gas-cooled metallic anode with a thin coating that creates a low effective work function.

The anode in a PETE converter has two major requirements: its work function should be low to allow a significant net voltage of the device, and its resistance should be low to avoid resistive loss. A solution can be a metallic anode with a thin coating that creates a low effective work function. Diamond, seems to have the lowest work function observed to date of 0.9 eV. The doping of Al into good light transmission ZnO anode can increase its conductance by several orders of magnitude. Also, nano-grating comparable with the de Broglie wavelength of the electron can change the electronic and electron emission properties of materials.

Studies on the influence of nano-grating structures on the properties of materials have shown that this process may lead to effects similar to those created by doping with donors. The resistivity values measured in Si-based nano-grating layers, for example, were approximately 10−2 Ohm cm, similar to those of Si semiconductors doped with phosphorus impurities having a volume concentration of 1018 cm−3 . It is almost independent of initial resistivity of samples: 5000 Ohm cm, 8.5-11.5 Ohm cm, or12-14 Ohm cm. The PETFE panels convert about 25% of the thermal energy into electricity. The remaining 75% is captured a thermal energy storage system, which can run a heat engine with 30% efficiency to produce electricity during off-sun hours. Total efficiency could be 50% [1].

A storage system prototype could be based on the TES design developed by Brayton Energy LLC, in which a hot fluid delivers its heat into a flowing bed of low-cost silica sand. The hot silica sand, at 715 °C, is collected in a hot storage tank mounted mid-tower. The cooled sand is collected in a cold storage tank near the bottom of the tower. From here it will be carried back up to the top of the tower via an insulated skip hoist. Heliostats collect incoming solar energy and focus it on three receiver sections located atop a tower. The first receiver absorbs 1/5 of incoming solar energy and transmits it into sCO2 at 575 °C [2].

3D-printed PETFE design

In the spiral or comb-like photon-enhanced converter designs, carbon nano-tube (CNT) ink printed on a dielectric substrate as a cathode is surrounded on both sides by a gate made of high dielectric constant and negative electron affinity (NEA) materials. Field-induced electron emission describes the quantum tunneling of electrons from a material surface into a vacuum under a strong electric field. The 3D-printed field-emission electron source recently developed at MIT has emission current 60 μA/cm2, start-up voltage 62 V and gate transmission as high as 99%. A synergy of optical, field and thermal excitation as well as a low-pressure cesium vapor in the inter-electrode gap improves the performance of a thermionic converter [3]..

The work-function lowering for semiconductors is traditionally achieved by coating surfaces with cesium and oxygen (Cs,O). By heating a few grams of material containing cesium, the pressure of cesium vapor within the vacuum insulation can be varied. However, toxic alkali metal-based coatings, has technological limitations due to thermal instability both of the emitting coating and of the semiconductor lattice itself. Surface texturing without the involvement of complicated lithographic steps and surface post-processing, represents a practical tool for an alternative approach. A new multi-junction solar cell with multiple p-n junctions separated by vacuum gaps allows using different semiconductor materials as cathode, gate and anode, activated to the state of effective negative electron affinity (NEA).

An in-plane gate electrode serving as an electron generator itself creates on the cathode surface an electrostatic field large enough to compensate space charge field and initiates TFE process. The PETFE power conversion efficiency can rich a quantum yield value which is is about 25%. The CO2 gas from the TFE anode at the temperatures of about 650°C heats sCO2 Brayton and steam Rankine cycles. This thermal radiation can photo-excite a significant amount of electrons to the cathode conduction band if the cathode or gate is made of a p-doped narrow-bandgap semiconductor, such as diamond film (Eg=1.54 eV), InSb (Eg=0.17 eV), GaSb (Eg=0.726 eV) or InAs (Eg=0.354 eV), where Eg is the bandgap energy [4-6].

The traditional PETFE converter consists of a p-doped narrow-bandgap semiconductor as the absorber, a wide bandgap semiconductor as the barrier, and metal anode electrodes. From the perspective of thermionic emission, the absorber is treated as a cathode with a barrier of Vc. The thickness of the gate is thick enough to absorb the incident solar radiation and is comparable to the electron diffusion length (Figure 1).

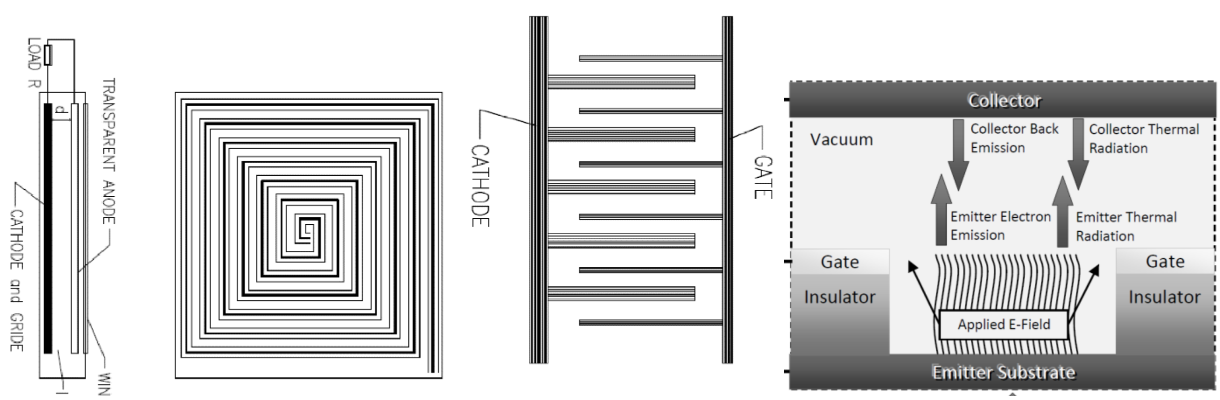

Figure 1. Front side illuminated spiral or comb-like PETFE solar energy converter

Figure 2 illustrates the small tower plant and PETFF concept test configuration based on the storage system developed by Brayton Energy, LLC.

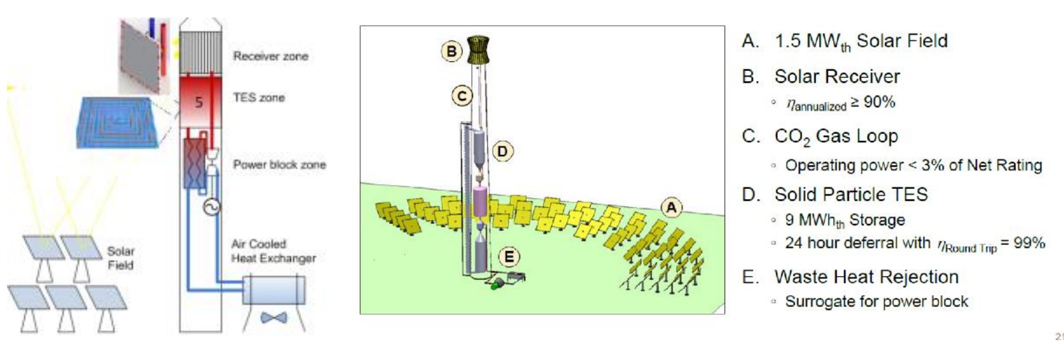

Figure 2. Small tower plant and Brayton Energy test facility [2].

Negative electron affinity can be developed for high quantum efficiency electrodes by a very thin Cesium layer on the surface in such materials as p-type GaAs and In-Ga1-xAs. Recently, phosphorus-doped diamond was reported to have a work function of 0.9 eV with thermal stability to at least 7650C. The Richardson coefficient, however, was very low indicating very high electrical resistance.

However, the original PETE has one critical drawback: the number of incident photons with energies larger than the bandgap value of GaN (Eg = 3.3 eV) comprises approximately 1% of their total quantity. This significantly decreasing the theoretical efficiency of this PETE. Also, significant problems are the high production cost of a single-crystal GaAs substrate as well as the technological problems in GaAs wafers' manufacturing.

The high current density of 105 A/cm2 close to the field emission limit was obtained from an electrically heated single horizontal carbon nano-tube (CNT). Due to various collective effects, the current density was 1.73mA/cm2 in CNT arrays at a bias voltage of 2.64V. At the electric field 5×105 V/m and turn on/off response times 150/500ns, it was a displacement current, rather than flow of charge [7].

As 3D-printed PETFE converter material is similar to that used in photovoltaic cells, their performances at elevated temperatures can be compared. The improved performance of the solid-state PETE converter at high temperatures is attributed to the simultaneous use of diffusion and ballistic electron transport to harvest both thermal and photon energy. A carbon nanotube (CNT) emitter formed as a CNT film grown directly on nickel–chromium alloy wire can be electrically heated to study this cocept.

A photon-enhanced converter based on the transmission-mode, GaAs photocathode with exponential-doping structure and thin anode is containing a large number of cooling micro-channels that serve as a receiver. The well known field emission physics is described by the Fowler-Nordheim based models developed for traditional bulk materials..The development of the Schottky thermal field-emission makes possible a novel field-emission converter design.

The one-dimensional integral equation approach to the solution of the Boltzmann equation has led to the short circuit current densities j=e*n*vav and open circuit voltage is about 1-2V, where e is the elementary electron charge, n is the electron densities and vav average electron velocity. If the electron clusters near anode have the speed of about 3*107 cm/s, we need about lO12cm-3 electron densities to obtain output current densities 1 A cm-2

Another aspect of PETFE converters is the ability to keep the anode at a temperature high enough for waste heat utilization, but not so high as to create a significant reverse current. Porous silicon nanostructures for perspective PETFE electrode can be controllable in terms of the bandgap modification that could be varied in a wide range between 1 and 3 eV thanks to the presence of the so-called quantum confinement effect. The, electrostatic nature of plasmon resonance in nano-particles and their negative dielectric permittivity values lead to the enhancement of local electric fields around nano-particles. localized surface plasmon resonance will be simultaneously excited on all nano-particles. Both the thickness and the period of the metal nano-particles affect the effective photon flux [8].

A quartz tube window provides a greater than five-percent efficiency benefit to the receiver by reducing both convection and radiation losses. The quartz absorbs long wavelength emissions from the cavity, while transmitting the visible solar input power. The quartz bundle as a window significantly reduces cavity receiver convection losses. In transmission PETE conversion that is a combination of two mechanisms for electron emission—thermal and photonic, the cathode is illuminated by concentrated solar radiation. A beam-down dish design includes: TES 5, PETFE cathode 7, anode 8 and gate 10, as shown in Figure 3.

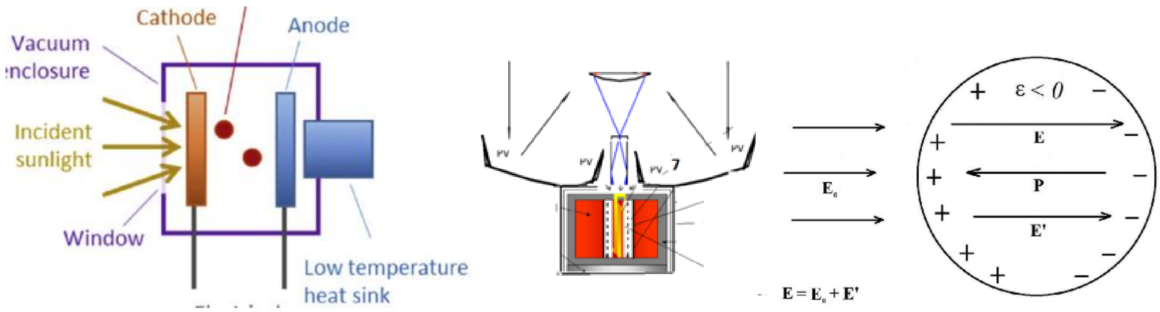

Figure 3. PETE converter, beam down concept and Ag nano-particle in external electric field.

Conclusion

We propose a new 3D-orinted solar-to-electricity converter with multiple p-n junctions separated by vacuum gaps that allow using different semiconductor materials as cathode, anode and gate activated to the state of effective negative electron affinity (NEA). The PETFE panels control heat transfer into and out of the TES. With vacuum off-sun insulation the thermal conductivity is lowered by a factor of 6 to 10, compared to conventional insulation materials. The COMSOL modeling of the converters could be based on the Lorentz Theory, which proved to be ahead of its time by hypothesizing before quantum mechanics that some disturbances, like waves, travel with particles through a vacuum without moving it [9].

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РОЗРОБКА ТА ДОСЛІДЖЕННЯ ПРОДУКТИВНОСТІ СОНЯЧНИХ ЕЛЕКТРОГЕНЕРАТОРІВ ПЛАСТИКОВИХ

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Створений та випробуваний сонячний електротеплогенератор пластиковий (СЕТГ-ПЛ) – гібридний модуль, який паралельно генерує електрику й тепло з сумарним ккд до 95%. Результати досліджень продуктивності у різних експериментальних умовах продемонстрували перспективність його впровадження.