THERMOPHOTOVOLTAIC SEMICONDUCTOR DEVICE

The present invention relates to the general area of generating carriers such as electrons and holes within semiconductors by the action of incident radiation, being more particularly concerned with radiation emanating from heated surfaces, and, in an important application, to the enhancement of such generation within photovoltaic devices and the like, due to the close proximity of the heated surface.

BACKGROUND OF THE INVENTION

In a common photovoltaic cell, a semiconductor p-n junction is formed close to the surface of the semiconductor material that forms the cell. When photons emitted by a light source such as the sun impinge on the cell surface, electron-hole pairs are created. These electron-hole pairs are separated by the space-charge potential that is a consequence of the p-n junction. The net result is a DC current. Thermophotovoltaics operate in a similar manner except that, instead of a light source, a surface at a higher temperature than the semiconductor material acts as the source of photons. In this case, thermal radiation is the mechanism of energy transfer and the temperature of the emitting surface which dictates the spectral composition of the radiation must be matched to the material and electronic properties of the semiconductor such as its bandgap in order to optimize conversion efficiency.

Prior thermophotovoltaic devices and systems have been designed such that the distance between the emitting surface and the cell surface is large relative to the characteristic wavelength of the thermal radiation. Hence, the thermal radiation transfer is characterised by the Stefan-Boltzman Law and its spectral composition by Planck's law.

CONFIRMATION COPY

MICROSCALE RADIATIVE HEAT TRANSFER

Turning now from the field of semiconductor devices, including photovoltaic cells and the like, to the general field of radiative heat transfer, in the classical theory of radiative heat transfer, the radiated power per area and per interval of wavelength of a flat surface in thermal equilibrium with its surrounding is given by Planck's Law. Integration of Planck's Law over all wavelengths yields the Stefan-Boltzman Law for black surfaces. Similarly this law governs the exchange of energy between two black surfaces.

Planck's Law predicts that a large portion of the radiative energy at a given temperature of radiating body will be around the wavelength of greatest spectral intensity "lambdamax". "Lambdamax" is predicted by the Wien Displacement Law. At shorter wavelengths the power falloff is very rapid whereas at wavelengths greater than lambdamax the falloff is much more gradual. At lower temperatures lambdamax occurs at longer wavelengths.

In the above classical theory it is assumed that the distances between radiating surfaces is large compared to the wavelengths of the energy involved. Planck himself imposed this condition on his derivation. Over the last several decades a small segment of radiative heat transfer theory and experiment has developed wherein the spaces between radiating solids are on the order of and smaller than the characteristic wavelengths of the radiation exchanged. There is experimental evidence to show that energy exchange between two surfaces (dielectric to dielectric or metal to metal) separated by a distance of the same order as the wavelength or less can be several times larger than at larger distances, and that the magnitude of this effect increases sharply with decreasing distance. Examples of such experiments are Cravalho, E.G. et. Al., Nov.1967, "Effect of Small Spacings on Radiative Transfer Between Dielectrics", Journal of Heat Transfer, pp.351-358; Hargreaves, C.M., 1973, "Radiative Transfer Between Closely Spaced Bodies", Philips Res. Reports Supplement No.5, pp.1-80; and Kutateladze, S.S. et.al., Aug. 1978, "Effect of Magnitude of Gap Between Metal

Plates on their Thermal Interaction at Cryogenic Temperatures", Sov.Phys.Dokl. 23(8), pp.577-578. Orders of magnitude increase with very small or "microscale" spacings were theoretically predicted by Polder, D. et.al., Nov. 1971, "Theory of Radiative Heat Transfer Between Closely Spaced Bodies", Physical Review B, Vol. 4, No. 10, pp.3303-3314 and Levin, M.L. et.al., 1980, "Contribution to the Theory of Heat Exchange Due to a Fluctuating Electromagnetic Field", Sov.Phys.JETP, Vol. 6, pp.1054-1063.

Underlying the present invention, as more fully delineated in my as yet unpublished thesis at the Massachusetts Institute of Technology entitled "Enhanced Semiconductor Carrier Generation Via Microscale Radiative Transfer; MPC – An Electric Power Finance Instrument Policy; Interrelated Innovations in Emerging Energy Technologies, dated June 1996, is my novel conceptual insight and discovery that these previously unrelated technologies of thermophotovoltaic energy conversion and of small spacing radiative heat transfer systems could synergistically be combined in such a manner as to enhance the generation of semiconductor carriers (electrons and holes) in semiconductor devices such as photovoltaic cells and the like, receiving radiation, such as photons, from a heated surface, through the use of very small gap juxtaposition of the surfaces of the device and the heated surface.

OBJECTS OF THE INVENTION

A primary object of the invention accordingly, is to provide a new and improved method of enhancing the generation of carriers (ex. Electrons and/or holes) in semiconductor devices and near their surfaces, receiving radiation from a heated surface, through the use of very small gap ("microscale") juxtaposition of the surface of the semiconductor surface or device and the heated surface.

A further object is to provide an improved thermovoltaic system.

Other and further objects will be explained hereinafter and will be more particularly delineated in the appended claims.

SUMMARY

In summary, from one of its broader aspects, the invention embraces a method of enhancing the generation of carriers in a semiconductor near its surface receiving radiation from a heated surface, that comprises, placing the surfaces in juxtaposition, and adjusting the space therebetween to micron scale separation.

More generically, the invention combines previously unrelated technologies of thermophotovoltaic energy conversion and of small spacing radiative heat transfer systems in such a manner as to enhance the generation of semiconductor carriers.

Preferred and best mode designs and implementations will later be detailed.

DRAWINGS

The invention will now be described in connection with the accompanying drawing, the schematic figure of which illustrates the novel principles of the invention as applied to an exemplary application of a thermophotovoltaic device.

PREFERRED EMBODIMENT(S) OF THE INVENTION

Referring to the drawing, a heated surface emitter of radiation, including photons, is schematically shown at 1 in the form of a substantially planar hot surface at temperature T_H, juxtaposed in accordance with the present invention, in very close proximity to a substantially parallel surface 2 of a semiconductor receiver of the radiation, such as a photovoltaic cell of

relatively cool temperature of T_C, as described on page 46 of my said thesis. Cell current collection contacts and grid (not shown) would be provided in the bottom or back surface or recessed from the front active surface of the cell.

The enhanced synergistic effect of the invention in terms of significant increases in carrier generation in response to the incident radiation from heated surface 1, is achieved by effecting the above-mentioned critical close proximity of the surfaces 1 and 2 with a micro gap (Evacuated Gap) on the order of 0.01 microns up to the order of about 1 micron, as presented on said page 46, and in some cases of longer wavelengths (as in cryogenic applications and the like) even up to the order of 100 microns as shown on page 77 of said thesis, 0.01-20 microns being a preferred range for most applications.

The fine adjustment of the crucial micron range separation gap between the surfaces 1 and 2 may be controlled as more fully described on pages 84-85 of my said thesis by such devices as piezoelectric controlled levelling stages or the like such as the Model 8095 of New Focus Corporation.

In view of the very small gap, moreover, vibration isolation may be required as by conventional isolation tables and the like.

While the invention has been described in connection with the example of a photovoltaic semiconductor device, it is evident that the carrier enhancement effect from close juxtaposition of a semiconductor surface and a heated surface is generically applicable and useful.

Instead of flat surfaces, as described on pages 66 and 67 of my thesis, patterns may be etched or otherwise formed into three-dimensional forms (channels, islands, etc.) to tailor the electromagnetic spectrum of the radiant energy being transferred to the juxtaposed semiconductor surface. There may then be a natural progression from one dimension, MTPV, i.e

controlling the distance between two surfaces, to three dimensions wherein in addition to the Microscale spacing, the properties of the surfaces as a function of the two lateral dimensions are also controlled. In summary, if x and y are in the plane of the Emitter and Receiver chip surfaces and z is perpendicular to them, then the degrees of freedom are: z between the chips, z within one or both chips, x and y within one or both chips, and x and y of one chip relative to the other.

Semiconductors include Si and binary, ternary, and quaternary compound semiconductors including InAs, InGaAs, and InGaAsSb and others

The heated surface, moreover, may, as described in said thesis, not only involve lattice and carriers at the same temperature, but also conditions where the carriers are at a hotter temperature than the lattice ("hot electrons") as through absorption of electromagnetic energy.

Further modifications will also occur to those skilled in this art, and such are considered to fall within the spirit and scope of this invention as defined in the appended claims.

CLAIMS

1 A method of enhancing the generation of carriers in a semiconductor surface receiving radiation from a heated surface, that comprises, placing the surfaces in juxtaposition, and adjusting the gap therebetween to micron scale separation.

2 A method as claimed in claim 1 wherein the gap is evacuated and the separation is adjusted to the order of from about 0.01 to 100 microns.

3 A method as claimed in claim 2 wherein the semiconductor surface comprises a relatively cooler photovoltaic device.

4 A method as claimed in claim 3 wherein the surfaces of the photovoltaic device and of the heated surface are substantially planar.

5 A method as claimed in claim 4 wherein one or both of the juxtaposed surfaces are patterned.

6 A method as claimed in claim 4 wherein in addition to controlling the separation between the surfaces, the properties of one or more of the surfaces in dimensions orthogonal and parallel to the separation are varied.

7 A combined radiation transfer and thermophotovoltaic device apparatus having, in combination, a photovoltaic cell surface and a heated radiating surface, the latter being positioned juxtaposed to the cell surface and separated therefrom by a gap of the order of microns or a fraction thereof.



8 Apparatus as claimed in claim 7 wherein the gap is evacuated and the separation is adjusted in the range of about 0.01 to 20 microns.

9 Apparatus comprising a combined semiconductor surface and a heated surface for impinging radiation thereupon to generate semiconductor carriers with the surfaces being supported in close juxtaposition separated by an evacuated gap of order of microns or a fraction thereof.

10 A method of enhancing the generation of carriers in a semiconductor surface receiving radiation from a heated surface, that comprises, emitting radiation from a heated surface of temperature T_H; coupling the radiation through an evacuated gap for reception by a relatively cool semiconductor surface maintained at temperature T_C, where $T_H > T_C$; and adjusting the thickness of the gap to the order of submicrons/ microns to achieve an enhanced increase in the semiconductor generation of charged carriers in response to the radiation coupled through the gap.

11 The method claimed in claim 10 wherein one or both of the heated and semiconductor surfaces is provided with material formed for tailoring the spectrum of the emitted radiation coupled through the gap.

12 The method as claimed in claim 11 wherein the material is provided along one or more of the X, Y and Z axes of either or both surfaces.

13 The method as claimed in claim 11 wherein either or both of the surfaces is provided with one of patterns, channels, islands and three-dimensional forms.

14 The method as claimed in claim 10 wherein the submicron/micron thickness is adjusted by controlling the levelling of the surfaces.

15 The method as claimed in claim 10 wherein the gap is isolated from vibration.

16 The method as claimed in claim 10 wherein the semiconductor is constructed to render it a photovoltaic device.

17 A method of enhancing the generation of carriers in a semiconductor surface receiving radiation from a heated surface, that comprises, juxtaposing the surfaces with a thermally insulative substantially lossless radiation-transmitting medium disposed therebetween; and adjusting the thickness of the medium therebetween in the submicron/micron range.

18 The method as claimed in claim 17 wherein the thermally insulative substantially lossless radiation-transmitting medium comprises an evacuated gap.

19 A combined radiation transfer and carrier-generating semiconductor apparatus having, in combination, semiconductor and heat-radiating surfaces, wherein the heat-radiating surface is operated at a temperature greater than that of the semiconductor surface; a thermally insulating and substantially lossless radiation-transmitting medium disposed between the surfaces for coupling the radiation from the heat-radiating surface for reception by the semiconductor surface; the thickness of the medium being adjusted to the order of submicrons/microns to achieve an enhanced increase in the semiconductor generation of charged carriers in response to the radiation coupled through the medium.

20 Apparatus as claimed in claim 19 wherein the medium comprises an evacuated gap.

21 A method of enhancing charged carrier generation in a semiconductor surface in response to incident heat radiation from a heat-radiation surface, that comprises,

combining the phenomenon of the increased heat radiation energy exchange produced at the interfaces between a pair of parallel surfaces brought closely together and wherein one surface is a heat-radiation generating surface, together with the exciting of charged carrier generation in a semiconductor surface in response to heat radiation, by directing such increased heat radiation energy exchange produced at said interfaces upon the semiconductor surface.

22 A method of enhancing the generation of electrical currents in a conductive or semi-conductive surface receiving radiation from a heated surface, that comprises, emitting radiation from a heated surface of temperature T_H; coupling the radiation through an evacuated gap for reception by a relatively cool conductive or semi-conductive surface maintained at temperature T_C, where $T_H > T_C$; and adjusting the thickness of the gap to the order of submicrons/microns to achieve an enhanced increase in the relatively cool surface generation of electrical currents in response to the radiation coupled through the gap.

23 The method claimed in claim 22 wherein the magnitude of the electrical currents generated is controlled by the adjustment of the gap.

24 The method of claim 23 wherein the energy enhancement achieved by the submicron/micron gap adjustment creates energy stimulation that is converted into the enhanced generation of the electrical currents.

25 The method of claim 24 wherein the relatively cool surface is a photovoltaic surface and the enhanced generation of the electrical currents manifests itself in the power output of the photovoltaic surface.

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