Amorphous Diamond Solar Cells

James C. Sung[*,1,2,3], Tun-Jen Hsiao[1], Ming-Chi Kan[1], Michael Sung[4]

Address: KINIK Company, 64, Chung-San Rd., Ying-Kuo, Taipei Hsien 239, Taiwan, R.O.C.
Tel: 886-2-2677-5490 ext.1150
Fax: 886-2-8677-2171
E-mail: sung@kinik.com.tw

[1] Kinik Company, 64, Chung-San Rd., Ying-Kuo, Taipei Hsien 239, Taiwan, R.O.C.
[2] National Taiwan University, Taipei 106, Taiwan, R.O.C.
[3] National Taipei University of Technology, Taipei 106, Taiwan, R.O.C.
[4] Advanced Diamond Solutions, Inc., 351 King Street Suite 813, San Francisco, CA 94158, U.S.A.

ABSTRACT

Silicon based photo voltaic panels are the mainstream of solar cells. However, there are intrinsic limitations of such devices for replacing power plants. The low conversion efficiency (<20%) would make it higher cost than generators run by fossil fuels. The repeated high temperature processes for extracting, purifying, and ingoting silicon actually wasted more electricity that may be recovered by solar cells. Additionally, silicon is not radiation hard so its crystalline structure will be gradually damaged by the bombardment of UV photons from the sun.

All these drawbacks can be overcome by using amorphous diamond as the electron generator in vacuum. Amorphous diamond contains the highest amount of atoms per unit volume (about 180/nm^3). Most carbon atoms are tightly held by distorted tetrahedral (sp^3) bonds. Because these distortions are all different, all carbon atoms have unique electron energies. The presence of numerous discrete energy states allows valence electrons to be excited by absorbing minute energies. Amorphous diamond is the only blackbody material that can absorb and emit low energy photons (e.g. 10 microns wavelength IR) and phonons (e.g. 100 C heat). If amorphous diamond is exposed in vacuum, the highly excited electrons can be emitted readily. Thus, amorphous diamond can be the most efficient thermionic material with the capability to convert up to half of sunlight's energy into electricity.

Experimental data has confirmed that amorphous diamond can absorb more energy than silicon when exposed to sunlight. The conversion efficiency for generating electricity can be boosted by narrowing the vacuum gap between the energy input anode and electron output cathode. If the gap is reduced to about one micron, the conversion efficiency can be much higher than that of silicon solar cells.

Keywords: amorphous diamond, solar cell, thermionic emitter, super entropy material

1 THE POLLUTED SOLAR CELLS MADE OF CRYSTALLINE SILICON

The mainstream solar cells are made of crystalline silicon. Although the cost for generating one KwH is 5-10 times of conventional fuel fossil power plants, crystalline silicon solar cells are thought to be environmentally friendly. However, crystalline silicon is typically produced from highly pure quartz that may be extracted from beach sand. The fact that white beach sand can only be produced after tens of million years weathering and washing implies that quartz is very stable. Consequently, it would require very high temperature (e.g. 1700℃ to reduce quartz to form metallurgical grade silicon. While silicon is reduced, 1.5 time of carbon dioxide is released that contributes to the green house effect. Moreover, the metallurgical grade silicon must be purified, again at high temperature. Eventually, the pure silicon is melted above 1410℃) to form either ingot for single crystal or casting for polycrystals. In all these high temperature process steps, high amount of electricity may be needed.

The crystalline silicon for making solar cells once get to a price tag of about $100/Kg. For making solar cells, about 0.5 mm thick, including cutting kerf, may be needed, so one kilogram of silicon may produce about 1 m^2 to exposed under sun. As the solar constant is about 1 Kw/m^2, and the average total efficiency one day of silicon solar cells as measured around the clock is less than 10%, we may expect that the power for one kilogram silicon material is about 0.1 Kw. Assuming that the power cost is about $0.05/KwH, the above 0.1 Kw solar panel would require about 2000 KwH or energy to produce. To pay back the bill, the silicon solar cells may have to run 20,000 hours or about 2.3 years! During this period, the governments have to subsidize the inefficiency of the electricity produced by such pollution causing silicon. Consequently, it is desirable to constructing solar cells by using more environmental friendly materials. One of such materials is amorphous diamond.

2 SUPER-ENTROPIC MATERIAL

Amorphous diamond appears to be contradictory term, like liquid crystal or glassy metal. Amorphous means non-crystalline and diamond implies crystalline. However, this terminology is meaningful because unlike silicon that forms only sp^3 bonds, i.e. diamond structure, carbon may form either sp^2 (graphitic) or sp^3 (diamond) bond. Although there is one form of amorphous silicon, there can be at least two forms of amorphous carbon, so amorphous diamond can be distinguished from amorphous graphite, and together they are amorphous carbon.

Amorphous diamond is formally known as tetrahedral amorphous carbon (tac), it is really a diamond-like carbon (DLC) that contains no non-carbon impurities (e.g. H). Amorphous diamond is essentially a chaotic carbon mixture with distorted sp^2 and sp^3 bonds. As such it possesses both metallic character of conductive graphite and semiconductor character of insulating diamond. Moreover, as each carbon atom is unique in its electronic state that is determined by the degree of distortion of its bonds. Hence, amorphous diamond contains numerous discrete potential energy for electrons. In fact, amorphous diamond may have the highest density of atomic occupancy (1.8×10^{23} per cubic centimeter) that is several times higher than ordinary materials (e.g. about four times of iron atoms or silicon atoms). Thus, amorphous diamond has the highest configuration entropy for both atoms and valence electrons.

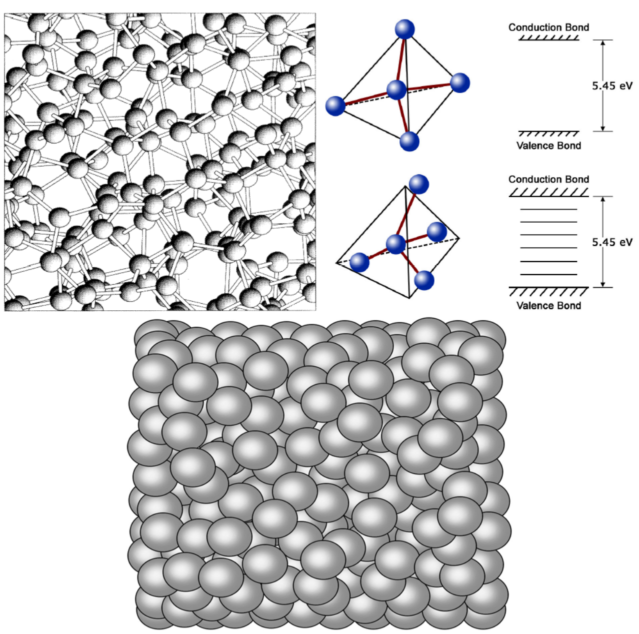

Fig. 1: The high atomic density and the unique way of distorting bonds for each atom makes amorphous diamond the material with the highest configurational entropy. As a result, amorphous diamond has the densest electron states that are discrete. This is in contrast of all materials that have either overlapped electron orbitals, as in the case of metal, or few discrete electron states, as in the case of semiconductors or insulators.

Amorphous diamond can be conveniently deposited by PVD methods, such as by sputtering or arc depositions. Due to the low temperature (<150 ℃) of deposition, amorphous diamond can be coated on most materials including metal, semiconductor, or even polymers. This flexibility makes amorphous diamond useful for many applications.

Due to such high configuration entropy of valence electrons, amorphous diamond is capable to advance electron energy by absorbing small increments of energy, such as by converting thermal energy (lattice vibration) to potential energy (electron state). If amorphous diamond is exposed in high vacuum (e.g. 10^{-6} torr), the energy state may be higher than vacuum state so amorphous diamond my emit electrons simply by heating. Because amorphous diamond has the highest discrete electronic states, it is the most thermionic material known.

3 THERMIONIC EMISSION

Even without high vacuum, amorphous diamond coated nickel electrodes of cold cathode fluorescent lamps (CCFL) used for back lighting can reduce significantly the turn-on voltage.

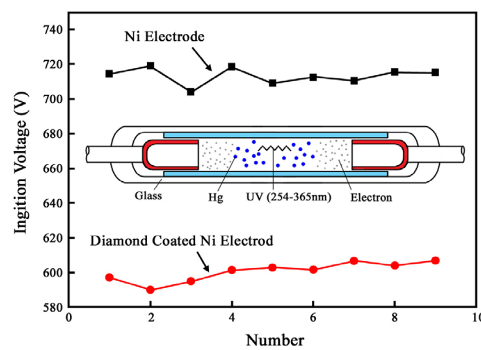

Fig. 2: The reduction of ignition voltage of CCFL by coating nickel electrodes with amorphous diamond.

Due to its exceptional ability to increase the potential energy of electrons by absorbing heat, amorphous diamond coated metal is highly thermionic.

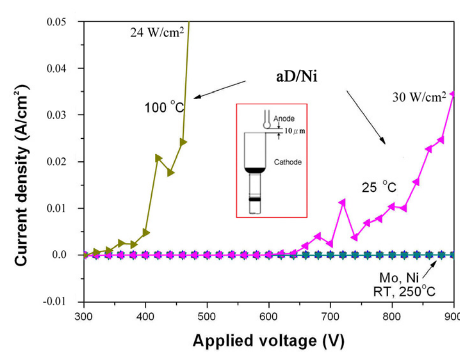

Fig. 3: The great enhancement of emitted current from amorphous diamond coated nickel electrode in CCFL by modest heating.

Based on the above thermionic effect, the effective work function, i.e. the activation energy for electron emission in vacuum, can be lower than 1 eV. This is the lowest of all materials that have effective work function higher than 2 eV. Due to this unique thermionic character, amorphous diamond can emit more current than even carbon nanotubes (CNT) that have a high work function, but with a nanometer radius to enhance the electrical field. Moreover, as amorphous diamond is solid in content, it can emit electrons at a much lower temperature than CNT that will concentrate electricity on the skin of the hallow structure. In fact, the skin of each CNT will burn out when the current exceeds 20 μA. As a result, CNT devices are not reliable (e.g. Samsung's CNT front panel display or Iljin's CNT backlight). In contrast, amorphous diamond field emission can be highly robust. This is particularly suited for display or backlight applications.

4 AMORPHOUS DIAMOND SOLAR CELL

The merit of amorphous diamond to convert either light or heat to electricity can be applied to solar cell panels or thermal electrical generators. For example, amorphous diamond was over covered coated on indium tin oxide (ITO), the transparent electrical conductor that was coated on a glass substrate. This panel was separated from another ITO coated glass by glass bead spacer. The gap was sealed around and the space was pumped down to high vacuum (10^{-6} torr). This panel was exposed to a xenon light that irradiated a spectrum with an energy output similar to solar constant (AM1.0 or $0.1 W/cm^2$). An external bias was applied and the electric current was monitored. It was demonstrated that the current increased substantially when light shone through or when amorphous diamond was heated up.

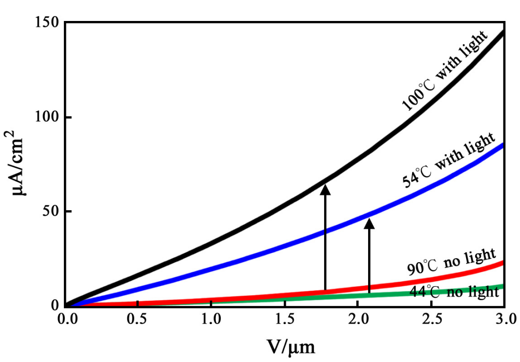

Fig. 4: Amorphous diamond can enhance electron emission in vacuum by light absorption and by thermal agitation.

When the applied bias was gradually reduced to zero, the current enhanced by xenon lamp was not dependent on the bias. Hence, the field emission could be triggered by sunshine directly without adding an external bias. However, the current density was too low to be useful as a solar panel unless the vacuum gap could be reduced further from 7 microns.

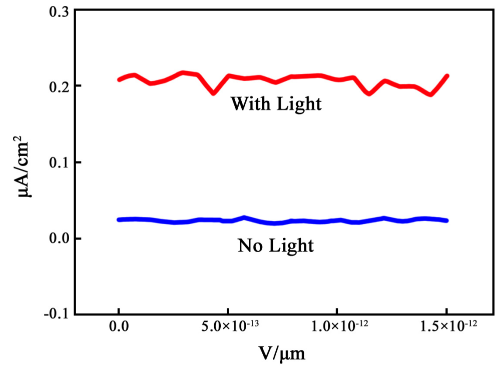

Fig. 5: The field emission became spontaneous when the external bias was reduced to zero.

When the vacuum was back filled with iodine, the current could be generated noticeably without applying the external field. This current was further increased by sensitizing amorphous diamond with a light absorbent dye. But even so, it was still low with the conversion efficiency.

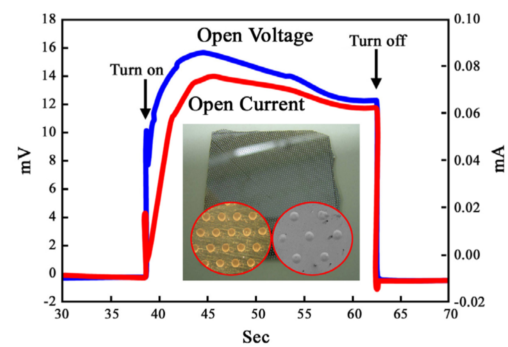

Fig. 6: The photo-electric effect of amorphous diamond when exposed to a xenon lamp (AM1.0) of about $0.1 W/cm^2$. In the experiment, the vacuum gap was back filled with liquid electrolyte of iodine.

The amorphous diamond solar cell was also constructed with a silicon layer in a hybrid design. In this case, no vacuum was needed. In one example, the nitrogen doped amorphous diamond was coated on boron doped silicon substrate. This hybrid design showed a dramatic increase in photo electricity, much higher than using a vacuum gap or back filed with a liquid electrolyte.

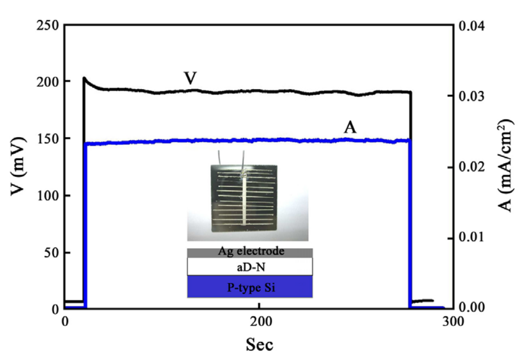

Fig. 7: The photo electric effect of nitrogen doped amorphous diamond coated on boron doped silicon layer.

When a monochrometer was used to filter the broad spectrum of the xenon lamp and the photocurrents of amorphous diamond coated silicon and silicon solar cell were measured and compared, the former exhibited a much higher value. Upon cooling the semiconductors to a cryogenic temperature of liquid nitrogen (70 K), the electrical current generated by light increased. Moreover, the increase was higher with shorter wavelengths (i.e. with higher energy). However, amorphous diamond coated silicon showed much higher cooling enhancement and also the blue shift of the peak wavelength.

The above observation demonstrated that amorphous diamond could absorb light and generate electricity more effectively than silicon. This is particularly attractive as amorphous diamond is radiation superhard and it would not be susceptible to UV damage. Amorphous silicon solar cells have the advantages of thin film and low cost, but the aging problem of UV damage makes it less useful so more costly crystalline silicon plates are used as solar panels. It would appear that amorphous diamond coating of amorphous silicon solar cells can boost both the energy conversion efficiency and the longevity of the service.

Due to the high electric resistance of amorphous diamond, the electric current it generated was dissipated as heat so the final output of electricity was significantly reduced. The dampening effect was greatly reduced by cooling the device at liquid nitrogen temperature. However, alternative methods by channeling out electricity rapidly once it is formed may also be effective to preserve the electricity generated. One example is to coat amorphous diamond on amorphous silicon layers and stack them together. Due to the thinness (e.g. 100 nm) of the amorphous diamond and amorphous silicon, the light absorbed by each layer can generate electricity independently. The electricity can then be channeled out readily due to the short distance of travel to reach the electrode. The combined electricity would retain most of the energy derived from sunlight.

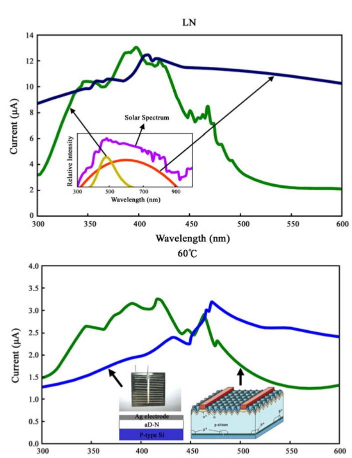

Fig. 8: The projected photo electrical current as a function of optical wavelength. Note that amorphous diamond could convert more current with IR irradiation than pure silicon. Moreover, the cooling enhancement of both energy and intensity was more obvious.

In summary, amorphous diamond has the highest density of discrete electronic states. This unique feature makes amorphous diamond particularly useful as energy converters, such as field emitters, solar cells, thermal generators, radiation coolers, and heat absorbers.

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