Amorphous Diamond Electron Emission for Thermal Generation of Electricity

James Chien-Min Sung*[,1,2,3], Kevin Kan[1], Michael Sung[5], Jow-Lay Huang[4], Emily Sung[6], Chi-Pong Chen[1], Kai-Hong Hsu[3] and Ming-Fong Tai[7]

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] National Cheng-Kung University, Tainan, Taiwan, R.O.C
[5] Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.
[6] Johnson and Johnson, Freemont, California, U.S.A.
[7] Department of Electronic Engineering, Wufeng Institute of Technology, Chia-yi 621, Taiwan, R.O.C.

ABSTRACT

Amorphous diamond represents a class of material of its own. It may be viewed to be a composite of metal (graphite) and insulator (diamond), but together they form a unique passage for electrons to flow through and to emit in vacuum. Amorphous diamond contains much defect so its electrical resistance is intermediate between metal and semiconductor. However, its ability to emit electrons in vacuum as cold cathode outstrips almost any class of materials. The easiness for electrons to flow through amorphous diamond and fly toward an anode across vacuum makes it an ideal material for electrical generator. In fact, the electricity generation can be so easy that amorphous diamond may become the most efficient solar cell ever invented. Moreover, by reversing the role of electricity generation, an amorphous diamond film may become an electron radiator. Such a radiator may dissipate heat much faster than the most advanced heat spreader (e.g., diamond substrate or heat pipe) currently being investigated.

Recent experimental results has confirmed that the current of electron emission in vacuum has increased two orders of magnitude when amorphous diamond is heated to 300 ^{o}C. Such a dramatic increase of current indicates that thermal energy can indeed shake off electrons in carbon atoms and accelerate them toward an anode across a vacuum. This phenomenon is consistent with the proposal that amorphous diamond can indeed be made of solar cells and/or heat spreaders.

Keywords: amorphous diamond, solar cell, diamond electrode, heat spreader

1 THE ELECTRON LADDER

Electronic energy states of atoms in a solid often form continuous bands. In the case of a metal (e.g., Cu), the conduction band overlaps with the valence band, so electrons can move up and down with no hindrance. In this case, although an electron can move to a higher orbital by gaining energy (e.g., by heating), it will drop back to the Fermi level instantly when the energy is lost. On the other hand, for an insulator (e.g., diamond), the conduction band is separated well above the valence band. Because of the presence of a large energy barrier in between, no electron will move to the conduction band unless it gains a quantum energy equal or higher than the band gap (5.45 eV for diamond). The band gap can prevent electrons from moving in either direction, so an electron once moves to the conduction band may stay there at least momentarily before falling down. If an insulator is doped with atoms of a different element (e.g., Li in diamond), a semiconductor is formed. In this case, an electron may assume an energy state that resides within the forbidden range of the host material. This electron may move up to the conduction band by acquiring a moderate amount of energy (e.g., 0.1 eV for Li in diamond) and stay there momentarily.

A diamond semiconductor contains a chemical dopant that can provide only one energy rung to the wide open band gap. Hence, the likelihood for an electron to climb up the energy barrier and reach the conduction band is slim. However, if a multitude of energy rungs can be inserted in the band gap, an electron may climb up the energy ladder with much less effort. In this case, more electrons may reach the conduction band at ease.

In order to insert this energy ladder, chemical dopants with different energies must be adapted, but known dopants for diamond are very limited (e.g., B, N, P) so they are not sufficient to create such an energy ladder. On the other hand, physical dopants with varying electron energies may be assembled to form such an energy ladder. The electron energy in a carbon atom can be varied by distorting the tetrahedral coordination of the diamond lattice in different degree. Hence, in an amorphous diamond that contains carbon atoms in distorted tetrahedral coordination, the band gap is full with energy rungs for electrons to occupy (Figure 1). Such energy rungs are known as defect band. Amorphous diamond possessing such an energy ladder is not an electrical conductor like graphite, nor is it an insulator like diamond, but a semi-metal that can transmit electricity intermittently.

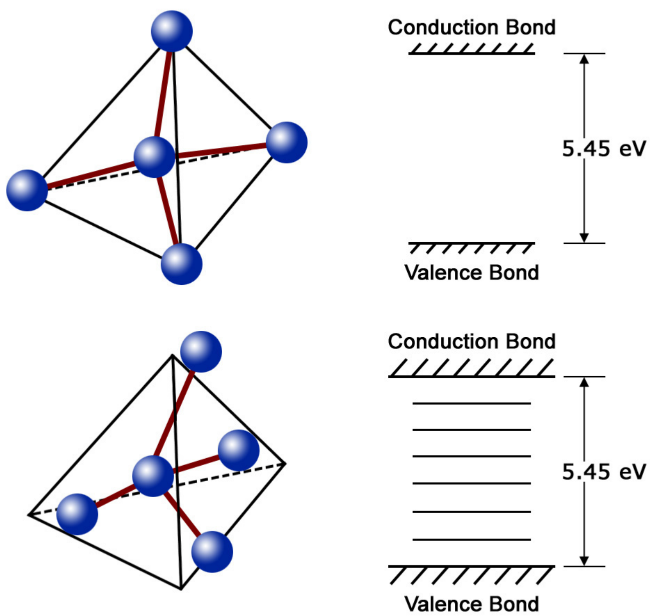

Figure 1: The symmetrical tetrahedral coordination of carbon atoms in diamond can form a wide band gap (top diagram), but the distorted tetrahedral coordination of carbon atoms in amorphous diamond will incorporate an energy ladder (defect band) in the band gap so electrons can climb up to the conduction band by leverage (bottom diagram).

In order to generate electricity in a solid, their electron must be excited to a higher energy. One way to do so is to emit electrons in vacuum and then collect these electrons by an anode. The electron energy at the Fermi level of an atom is much lower than that in vacuum. The difference between the two is known as work function that is the energy barrier to be overcome for an electron to enter vacuum. However, if an electron can climb up the energy ladder to reach the conduction band, its energy is now close to the vacuum level and hence with a little help from an external field, it could fly readily toward an anode across vacuum. Thus, for electrons to emit in vacuum from a metal, a large energy must be acquired (e.g., by heating to a high temperature as in the case of cathode ray) to overcome the work function, but very little energy may be needed to shoot electron out in vacuum from an amorphous diamond (e.g., by heating to a low temperature). In the case of diamond, unless there is a passage for electron to move through, no electron will be emitted.

When a solid is irradiated by a spectrum of electromagnetic radiation (e.g., by bathing in sun shine), the photon energy is absorbed by both electrons and atoms. If only electrons acquire the energy, the electrons will move with no resistance so the solid is a superconductor of electricity. On the other hand, if only atoms acquire the energy, the phonons will transmit with no hindrance so the solid is a superconductor of heat. In almost all cases, the light energy is distributed between excited electrons and vibrating atoms so the solid is not a superconductor of either electricity or heat.

The material will respond differently upon the impingement of electromagnetic radiation. For an opaque metal, photons can agitate atoms and force some electrons to move, for transparent diamond, most photons will pass through without being absorbed, and for doped silicon, some photons will be absorbed to form free electrons. However, an amorphous diamond will convert a significant amount of heat into the kinetic energy of electrons. In essence, a thermal electric effect is in action. The conversion of low thermal energy to high electricity energy seem to defy the second law of thermodynamics, but this apparent violation is explained as higher energy phonons are dissociated into lower energy phonons so the entropy in the form of heat is produced at both cathode and anode. Different materials may generate electricity from electromagnetic radiation based on different mechanisms.

2 AMORPHOUS DIAMOND THERMAL GENERATOR

The idea that diamond micro tips may be used as a solar cell was first proposed by Fisher. According to this model, a micro tip array made of boron doped diamond may be used as an efficient field emission device. The current can be induced by incorporating a gate anode for the application of an external field. The diamond microtips are mounted on a cathode. Fisher proposed to heat these diamond micro tips to about 1000 ^{o}C by focusing the sun light on a heat absorber that is coated on the cathode. He estimated that such a solar cell may achieve an efficiency as high as 50% that is at least double the energy conversion efficiency of the most advanced semiconductor solar cells currently available (e.g., made by GaAs).

The nano-tipped amorphous diamond has a diamond tip density about ten thousands times more than above mentioned micro-tipped doped diamond. Moreover, each tip is also much sharper and hence with a higher concentration of electrical field intensity. Hence, nano-tipped amorphous diamond can generate much more electricity than micro-tipped doped diamond.

Furthermore, the electrical resistance in amorphous diamond is much lower than doped diamond due to its high defects concentration. In addition, amorphous diamond can be deposited like spray painting, hence it is much cheaper to produce. In contrast, micro-tipped diamond relies on sophisticated lithography technology that is not only slow but also costly. Hence, amorphous diamond solar cells would be much more practical to be mass produced. The schematic of the design of an amorphous diamond solar cell.

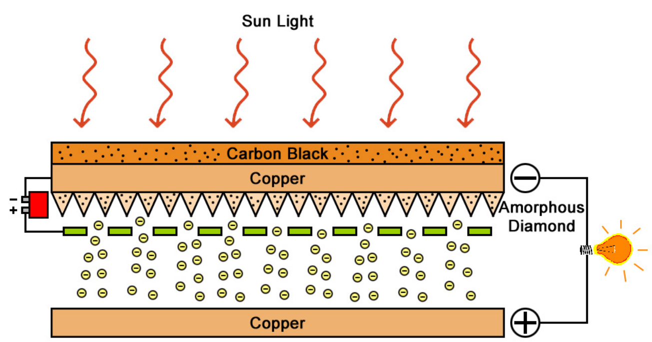

Figure 2: The schematic design of an amorphous diamond solar cell that may be operated at a temperature as low as 300 °C. The energy conversion efficiency may be up to 50%. Although this drawing portrayed a triode design, the two anodes may be combined in such a way that electrical current is drawn mostly from the heat rather than from the applied field.

The above solar cell is based on sharp nano-tips of carbon for efficient electron emission. Similar concepts may also apply by using carbon nanotube (CNT) bundles for shooting out electrons in vacuum. However, the emission of CNT bundles has several drawbacks. Firstly, the electrical resistance various among different CNTs, so the distribution of electrical current is intrinsically uneven. Secondly, CNTs are hallow tubes so electrons migration tends to concentrate on the thin wall. As a consequence, the tubes can be overloaded and burn out easily. Thirdly, the electrostatic repulsion can force CNT to erect periodically. Such movements make CNTs susceptible to fatigue deterioration. Hence, the aging effect of electron emission is inevitable.

In contrast, the electron emission performance using amorphous diamond nano-tips is much more reproducible. Moreover, amorphous diamond can be readily coated in large area at very low temperature (<150 °C) that is significantly cooler than the deposition temperatures (>600 °C) of CNTs. The lower cost combined with lower process temperature make the amorphous diamond a practical choice for industrial applications (e.g., to coat on the transparent conductor of ITO or on LCD glass panels).

In summary, amorphous diamond and CNT nano-tips may be used as solar cells. They may also be coated on panels that line up a heat producing system (e.g., an incinerator or even a nuclear power reactor) for electricity generation (Figure 3). Such a power generator does not contain moving parts that are typical for most power generators (e.g., turbine machine). The quiet power generator is not only maintenance easy, but also environmentally friendly.

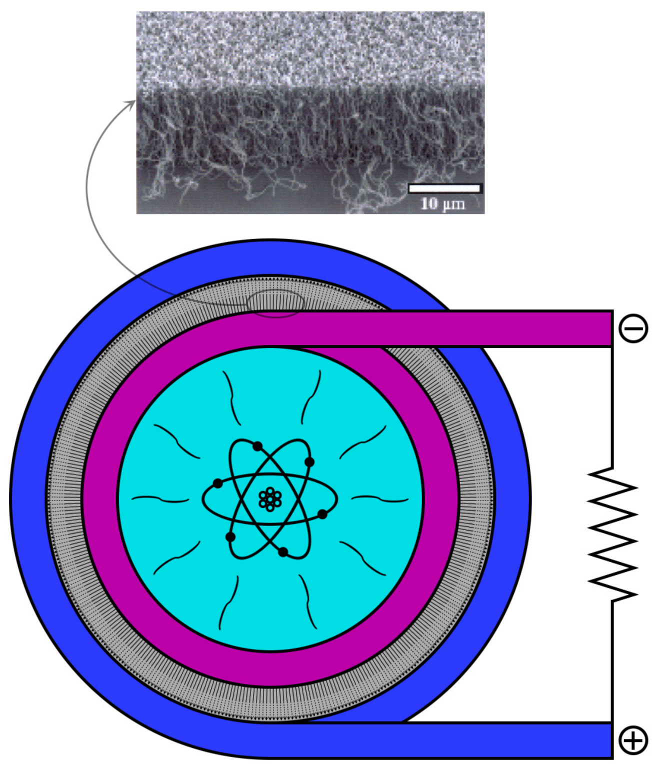

Figure 3: The idea of making a nuclear power plant safe by using amorphous diamond or CNT nano-tips to convert heat to electricity.

3 CONCLUSION

Amorphous diamond nano-tips (or CNTs) can be efficient electron emitters in vacuum. The easy for electrons to flow through the circuitry can make them the ideal thermal generator. This energy lever can allow low energy phonons to accumulate their energy and move electrons to fly across vacuum. The accumulation of phonon energy may appear to circumvent the second law of thermodynamics but in reality more lower energy heat are generated at both cathode and anode so the entropy of the entire system still rises. The nano-tip electron emitters envisaged can generate electricity from a variety of heat sources (sun light, incinery, hot spring, burning of coal, nuclear reactor…etc.). Moreover, they can be used as efficient chilling surfaces. Such surfaces are indispensable for future generations of computer CPU, high power electronics, laser diode, and MEM devices, to name just a few examples of exotic applications.

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