

# Amorphous Diamond as a Thermionic Material

James C. Sung<sup>\*,1,2,3</sup>, Ming-Chi Kan<sup>1</sup>, Tun-Jen Hsiao<sup>1</sup>, Ying-Tung Chen<sup>4</sup>, Michael Sung<sup>5</sup>

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

<sup>1</sup> Kinik Company, 64, Chung-San Rd., Ying-Kuo, Taipei Hsien 239, Taiwan, R.O.C.

<sup>2</sup> National Taiwan University, Taipei 106, Taiwan, R.O.C.

<sup>3</sup> National Taipei University of Technology, Taipei 106, Taiwan, R.O.C.

<sup>4</sup> Department of Mechanical Engineering, Chung Cheng Institute of Technology, Tahsi, Taoyuan 33509, Taiwan, R.O.C.

<sup>5</sup> Advanced Diamond Solutions, Inc., 334 6<sup>th</sup> Street, Suite 4, San Francisco, CA 94103, U.S.A.

## ABSTRACT

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, amorphous diamond contains numerous discrete potential energies for electrons. In fact, amorphous diamond may have the highest density of atoms ( $1.8 \times 10^{23}$  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.

Due to the distribution of discrete electronic energies with high density, amorphous diamond is uniquely capable to generate electricity and emit radiation. It has been demonstrated that amorphous diamond can be made as silicon free solar cells, front panel display field emission source, sensitive thermal sensing by IR detection, and perfect black body for energy conversion. Various amorphous diamond devices are being fabricated to exploit the superb properties of amorphous diamond.

**Keywords:** amorphous diamond, field emission, black body, front panel display, infrared detection

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 atoms ( $1.8 \times 10^{23}$  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.

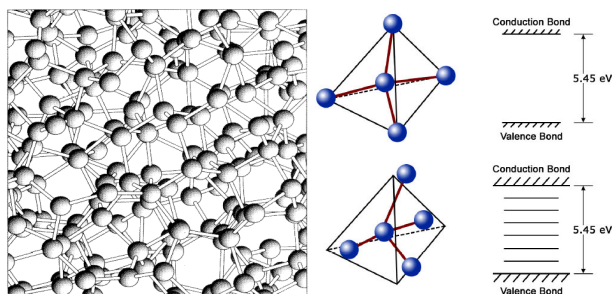


Fig. 1: The high atomic density and the unique way of distorting carbon bonds for each atom makes amorphous diamond the highest entropy material with the densest discrete atomic positions deviated from a crystalline lattice, and the most discrete electronic states of all materials.

Due to such a 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 may emit electrons simply by heating. Because amorphous diamond has the highest discrete electronic states, it is the most thermionic material known.

In general, materials fall in three camps, conductor, semiconductor and insulator, amorphous diamond is an atomistic mixture of all, so electrons can pass through it and be emitted in vacuum. By contrast, all other materials will stop electrons either inside the crystal lattice (e.g. an insulator) or on the surface (e.g. a conductor). The unique ability for amorphous diamond to emit electrons in vacuum by receiving low levels of energy makes it the excellent of field emitter with very low apparent work function. Amorphous diamond can be coated on metallic substrate by cathodic arc process to become a useful field emitter in vacuum.

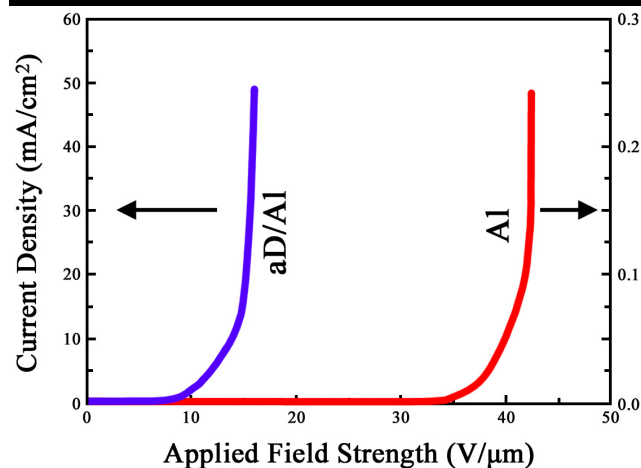
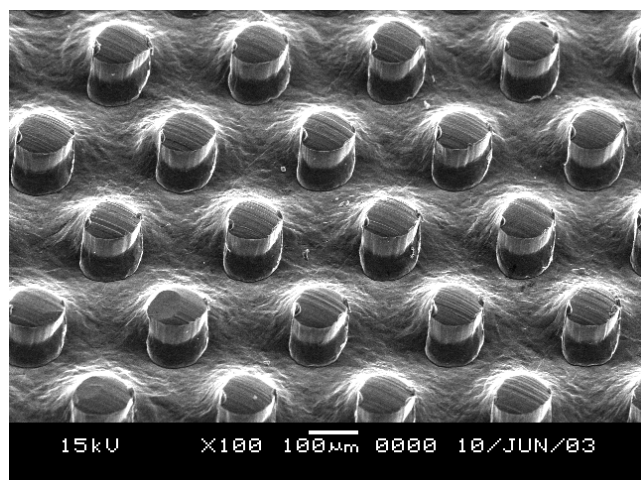


Fig. 2: The dramatic enhancement of emission current by coating amorphous diamond on aluminum cathode with bumps.

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.

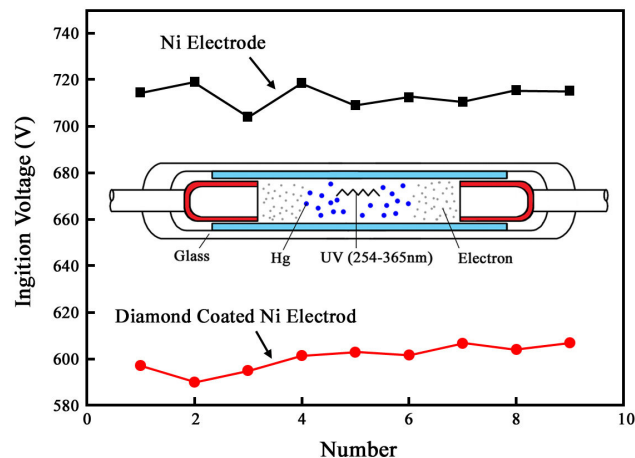


Fig. 3: The reduction of ignition voltage of CCFL by coating nickel electrodes with amorphous diamond.

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

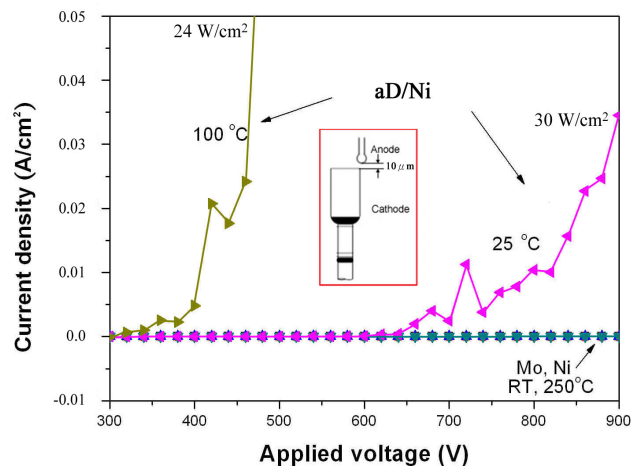


Fig. 4: The great enhancement of emitted current from amorphous diamond coated nickel electrode in CCFL by modest heating.

Materials fall under two camps: electrical conductors (metals) can conduct heat (phonon), but not emit heat (IR), and electrical insulators (ceramics) are just the opposite. However, amorphous diamond is both the thermal conductor and thermal emitter. Amorphous diamond is not only thermionic, it is also the perfect black body. Typically a metal has a low emissivity (e.g. 2%), but an insulator has a poor thermal conductance (e.g. 10  $\text{W}/\text{mK}$ ), so both of them cannot sustain the emission far infrared from a warm surface. However, amorphous diamond has

a thermal conductivity (about 500 W/mK) that is even higher than the best metal (420 W/mK for silver), and its emissivity is nearly 100%. It was measured that at a temperature as low as 70°C, the sustained heat emission was 0.088 W/cm<sup>2</sup>, this equals to what predicted by Stefan-Boltzmann's equation ( $5.67 \times 10^{-8} T[K]^4/m^2$ ) for black body. This implies that amorphous diamond has an emissivity of about 100% and the emission is not limited by its thermal conductivity. The exceptional ability to emit heat makes amorphous diamond an excellent thermal radiator for cooling high-powered LED.

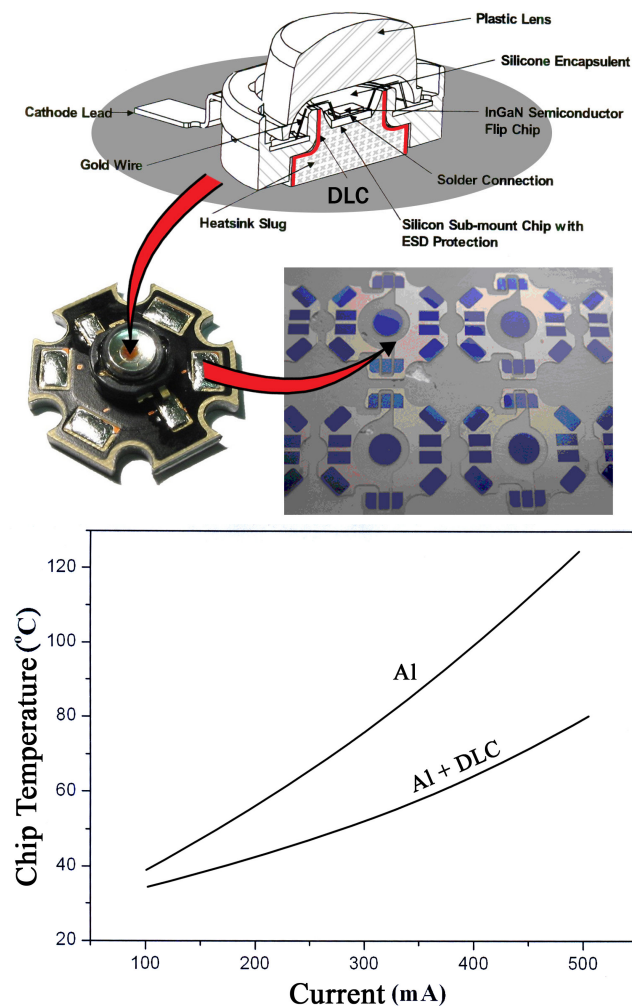


Fig. 5: The cooling of LED junction temperature by coating amorphous diamond on the surface of its aluminum substrate heat spreader.

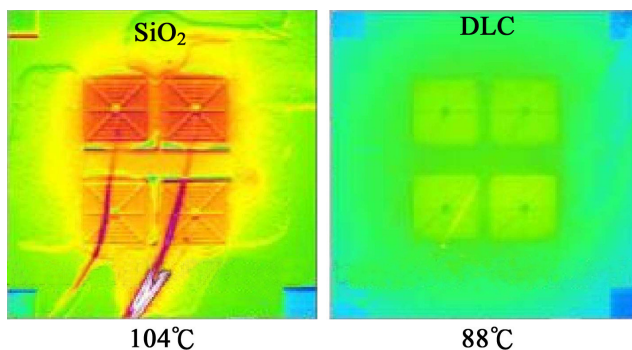


Fig. 6: The dramatic cooling effect by replacing silicon with an oxide coating with DLC coating for the submount of LED that was operated at 350 mA.

As the black body is reversible, amorphous diamond can be used as the heat absorber for applications related to advanced thermal imaging of infrared source or mundane water heating by absorbing sunlight.

The attribute of amorphous diamond to convert either light or heat to electricity may be used to make solar cells or thermal electrical generators.

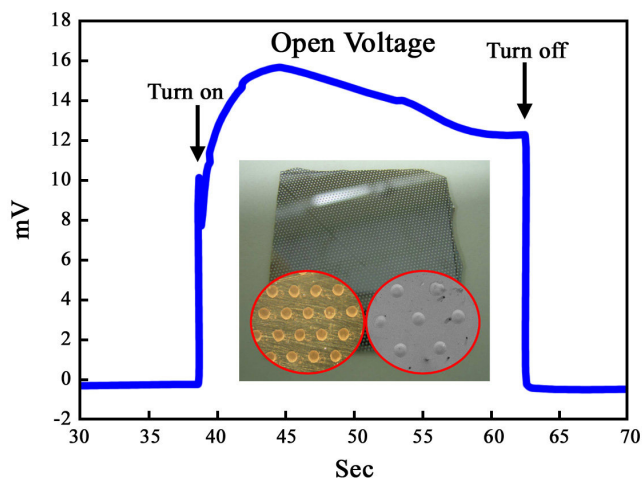


Fig. 7: The opto-electric effect of amorphous diamond when exposed to a xenon lamp (AM1.0) of about 0.1 W/cm<sup>2</sup>. In the experiment, amorphous diamond coated ITO glass was separated by 7 microns from an uncoated ITO glass with isolated glassy spacer (shown as dots).

The sensitive field emission and thermionic emission of electrons by amorphous diamond would make it an ideal coating material for Spindt (metal spikes) array that may be used for front panel displays. Such field emission displays will have the lowest operational power and panel temperature.



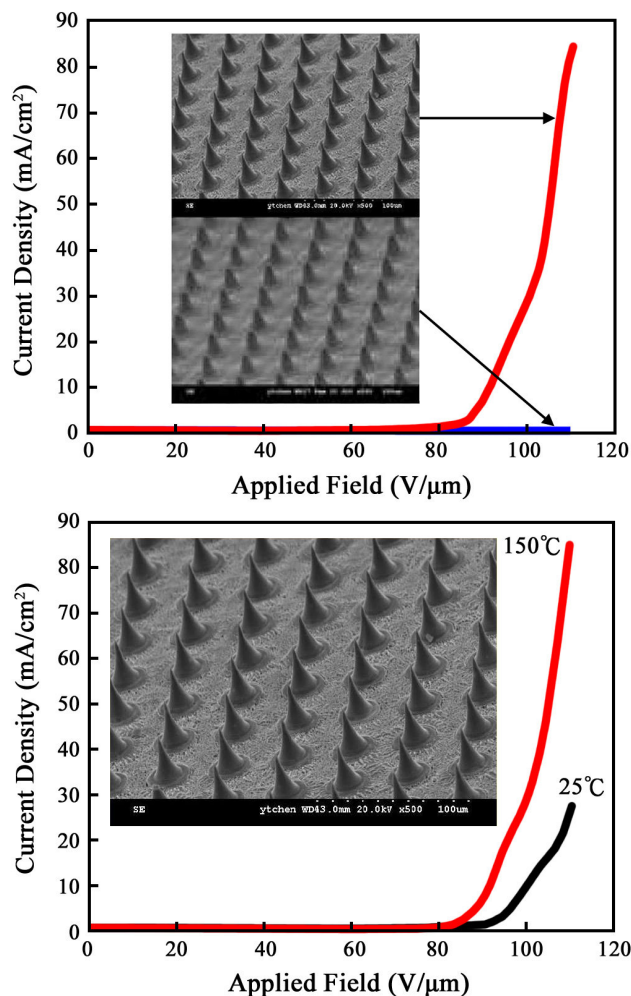


Fig. 8: The field emission of amorphous diamond coated nickel alloy cones can be enhanced by either sharpening the cone tips (upper diagram) or by modest heating (lower diagram).

In summary, amorphous diamond has the highest configuration entropy of electronic states, as a result, it is uniquely capable to emit electrons in vacuum upon receiving a low bias or simply by heating. Such unique properties makes amorphous diamond useful for a variety of applications such as field emitters, solar cells, thermal generators, radiation cooler, and heat absorbers.

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