

## **ELECTRONIC POWER SYSTEM APPLICATION OF DIAMOND-LIKE CARBON FILMS**

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### **ABSTRACT**

A prototype manufacturing technology for producing high volume efficiency and high energy density diamond-like carbon (DLC) capacitors has been developed. Unique dual ion-beam deposition and web-handling systems have been designed and constructed to deposit high quality DLC films simultaneously on both sides of capacitor grade aluminum foil and aluminum-coated polymer films. An optimized process, using inductively coupled RF ion sources, has been used to synthesize electrically robust DLC films. DLC films are amorphous and highly flexible, making them suitable for the production of wound capacitors. DLC capacitors are reliable and stable over a wide range of AC frequencies from 20 Hz to 1 MHz, and over a temperature range from  $-50^{\circ}$  C to  $300^{\circ}$  C. The compact DLC capacitors offer at least a 50% decrease in weight and volume and a greater than 50% increase in temperature handling capability over equal value capacitors built with existing technologies. The DLC capacitors will be suitable for high temperature, high voltage, pulsed power and filter applications

**Keywords:** Diamond-like carbon, capacitor, high energy density, high volume efficiency

### **1.0 INTRODUCTION**

Capacitors are a pervasive technology in every military and commercial application. Millions are used in electronic power systems and are considered to be a critical link to a common area of failure. Capacitors often fail under raised temperature conditions which may be due to lowering of the voltage breakdown strength, increase in dissipation factor and problems associated with drift of the dielectric constant. Diamond-like carbon (DLC) possesses unique properties of high dielectric strength, high resistivity, low loss, high decomposition temperature, chemical inertness and radiation hardness. It has been demonstrated that very thin (0.5  $\mu$ m) DLC films can be deposited directly onto smooth aluminum surfaces with good adhesion and that amorphous DLC films are highly flexible, making them suitable for the production of wound capacitors. Increased performance and reduction of capacitor size have been the main goals of our research in diamond-like carbon (DLC) dielectrics [1-2].

### **2.0 DEVELOPMENT OF DIAMOND-LIKE CARBON FILM CAPACITORS**

#### **2.1 Dual Ion-Beam Deposition of DLC Films**

A unique dual ion-beam deposition system was used for the deposition of high quality DLC films on both sides of capacitor grade aluminum foil and metallized polymer films in a continuous feed mode inside a class 100 clean room environment [3]. Highly reactive hydrocarbon ions were generated by two 6 cm x 22 cm linear inductively coupled RF (13.56 MHz) ion guns. The DLC films were produced by the impact of these ions onto the

aluminum foil surface or metallized polymer films. A quadruple mass spectrometer was used to monitor the plasma ion compositions during the deposition for quality control.

The dual ion-beam deposition system consisted of two 370-liter (61 cm in diameter by 102 cm long) stainless steel chambers that were bolted together; each was fitted with an ion source to coat one side of the aluminum foil. Each chamber was pumped by two Varian 1000 liter/sec. turbo pumps and backed by three Varian 600 l/min tri-scroll roughing pumps. A 70 liters/sec turbo booster pump was installed in one of the chambers for pumping the quadruple mass spectrometer. The background and deposition pressures of the system were  $10^{-5}$  and  $10^{-2}$  Pa, respectively. The web-handling system was housed in a stainless steel chamber (36 cm in diameter by 183 cm long), which connected the two ion source chambers together. A computer data acquisition and control system furnished with LabView software was implemented for the complete automation of the entire dual ion-beam deposition system.

The gases used were methane and hydrogen. An in situ quadrupole mass spectrometer was used to monitor the ionic species during the deposition. The predominant ion in the plasma was  $\text{CH}_3^+$ . The ion beam energy was varied over the range of 50 eV to 1000 eV, and films of varying thicknesses over the range from 0.3 to 0.8  $\mu\text{m}$  were deposited.

The chemical composition of DLC films was measured by Rutherford back-scattering (RBS) and hydrogen forward scattering. The film thickness of the DLC films was measured by a step profilometer (DekTak III) and by ellipsometry. The surface morphology and pin hole distribution were characterized by optical spectroscopy and atomic force microscopy.

## 2.2 Fabrication of DLC Test Capacitor

A method was developed for the fabrication of parallel-plate test capacitors on silicon wafers, on glass and on quartz substrates using two levels of metal electrodes, which were deposited through shadow masks. The parallel plate capacitors were produced by the deposition of aluminum dots through a shadow mask after the DLC film was deposited on the metallized substrates or aluminum foil.

## 2.3 DLC Test Capacitor Measurement

Electrical connections to the test capacitors were made with two probes on a standard probe station, in such a way that the probes touched the lower and upper aluminum electrodes of the capacitor. The electrical properties of the DLC films were determined by performing three sets of measurements: (a) capacitance as a function of frequency, (b) leakage current as a function of applied voltage, and (c) capacitance and leakage as functions of environmental conditions.

From the knowledge of the area of the capacitor, the DLC film thickness and the capacitance value, the electrical properties of the films such as dielectric constant, D.C resistivity and breakdown strength were obtained.

## 2.4 Electrical Quality of DLC Films

The deposited DLC films were amorphous and flexible, and had optically smooth surfaces. The electrical properties of capacitor grade DLC films were determined to be: dielectric constant of 3.3, breakdown strength of 7 MV/cm, and D.C. resistivity of  $> 10^{15}$  ohm-cm. The chemical composition of the films was found to be 55.2 at. % C, 43.3 at. % H, 1.4 at. % Ar, and trace levels of metals of  $\sim 0.014$  at. %.

## 2.5 Temperature Dependence of DLC Film Capacitors

The DLC capacitors were tested at various temperatures from  $-50^{\circ}\text{C}$  to  $400^{\circ}\text{C}$  over the frequency region of 20 Hz to 1 MHz. Using a high temperature test station, the temperature characteristics of DLC film coatings on aluminum foil were also studied. For the high temperature tests, the measurements were conducted under vacuum ( $10^{-3}$  torr). The frequency dependence of the capacitances and dissipation factors of the DLC capacitors was

measured from 25<sup>0</sup>C to 400<sup>0</sup>C. Figures 1 shows an example of capacitance variation for various temperatures. This figure indicates that the capacitors do not lose their initial characteristics up to 400<sup>0</sup>C.

For low temperature testing, sample capacitors (DLC158\_S1\_AL\_C39) were placed inside a chamber maintained at -50<sup>0</sup>C and LCR measurements were performed. The DLC film capacitance at -50<sup>0</sup>C was found to be the same as the room temperature value within measurement error over the frequency range of 20 Hz to 1 MHz. At the low temperature of -50<sup>0</sup>C, the dissipation factor was almost constant around 5E-3, whereas at room temperature the value was higher (1E-2 ~ 5E-3). This result indicates that DLC film capacitors can work at low temperatures as well as (or better than) at normal room temperature.

In this way it was established that the DLC capacitors can be operated from -50<sup>0</sup>C to 300<sup>0</sup>C.

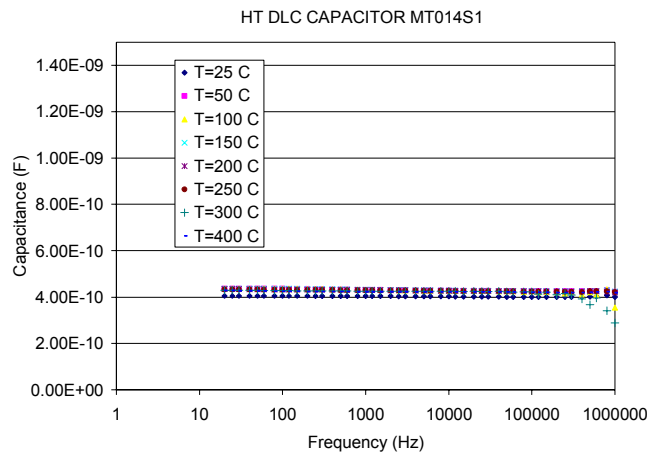


Figure 1 DLC capacitance as a function of frequency for various temperatures

## 2.6 Storage Life of DLC film Capacitor

In order to test the effects of ambient air on DLC capacitors, three DLC parallel plate capacitors were fabricated and measured in July 1996. These capacitors were stored in ordinary ambient air for two years. The electrical characteristics of the DLC films were measured again on March 26, 1998. After two years in ambient air, the properties of these DLC capacitors had not changed with time. Subsequently, the capacitance was measured at various temperatures in the range of 25 to 100<sup>0</sup>C, and found to remain essentially constant.

Another DLC capacitor was tested after five years of storage in air. No special storage conditions were used. The frequency dependence of the capacitance before and after five years was found to be the same. These results generally show that DLC electrical properties do not change appreciably over a 20-60 month period.

## 2.7 Effects of Oil on DLC film Capacitors

Some type of oil is always used in conventional capacitor manufacturing processes in order to remove air gaps from between the different layers in the capacitor. Air gaps may exist in the tightly wound DLC capacitors, and result in reduced capacitance value, as well as decreased breakdown strength. In order to study the DLC behavior with oil, DLC deposited aluminum foils were immersed in four different kinds of oil for more than a day. The oils used were mineral oil, vegetable oil, castor oil and canola oil. It was found that these oils did not cause the DLC to peel from the aluminum foil surface nor damage the DLC film. It also demonstrated that capacitance, insulation resistance and breakdown voltage of DLC capacitors did not change with or without the oils.

### 3.0 MANUFACTURING TECHNOLOGY

A compact capacitor winding system, consisting of a motorized film winder and two film supporting posts, was used to produce short-length DLC capacitors for testing. Several DLC capacitors were produced by rolling a pair of DLC coated aluminum foils. The capacitors were tested for capacitance and power dissipation factors. The capacitance values remained steady with variation of the AC signal frequency over the range 20 Hz to 1 MHz. Also the power dissipation factors were found to be quite low.

### 4.0 CONCLUSIONS

A prototype manufacturing technology for producing high energy density DLC film capacitors has been designed, constructed and verified. DLC is an amorphous, flexible film that can be deposited at a low temperature on both sides of capacitor grade aluminum foils or aluminum coated polymer films. DLC films possess low dissipation factor, high resistivity, high breakdown strength, and chemical inertness. These properties make DLC films suitable for producing high energy density pulse power capacitors. Conventional film capacitor manufacturing technology can be adapted for producing high energy density DLC capacitors. Moreover, DLC capacitors are reliable and stable over a wide range of AC frequency from 20 Hz to 1 MHz, and over the temperatures range from  $-50^{\circ}\text{C}$  to  $300^{\circ}\text{C}$ . The compact DLC capacitors offer a 50% decrease in weight and volume, and a greater than 50% increase in temperature handling capability over equal value capacitors built with existing technologies. The tubular capacitor form lends itself easily to large-scale, low-cost manufacturing. The DLC capacitors will be suitable for high temperature, high voltage and pulsed power applications.

### 5.0 ACKNOWLEDGEMENT

This research was conducted under K Systems Contract No. F33615-98-C-2818, sponsored by Air Force Research Laboratory, Power Division, Wright Patterson AFB, OH under SBIR Phase II Program, and was partially supported by the NASA Glenn Research Center and the Army Research Laboratory.

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