Mechanical and Semiconductor Properties of Nanophase Amorphic Diamond Coatings for High Power Electronics

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ABSTRACT

Mechanical and semiconductor properties of nanophase amorphic diamond are employed to improve the high power photoconductive semiconductor switch longevity by coating the switch cathode or anode areas or both. In this work issues concerning the switch longevity were studied by fabrication and testing the GaAs photoconductive switches treated with the nanophase amorphic diamond coatings. The tunneling of electrons from diamond to GaAs during the off-state stage of operation provided pre-avalanche sites that diffused conduction current upon switch activation. A significant improvement in switch lifetime was demonstrated by testing the diamond-coated switch performance in a prototype pulser.

Keywords: Nanophase amorphic diamond, rectifying heterojunctions, photoconductive semiconductor switch.

1 NANOPHASE DIAMOND

Nanophase amorphic diamond coatings have been produced at the University of Texas at Dallas (UTD) by accelerating and quenching intense laser plasma of C^{3+} and C^{4+} onto a substrate at room temperatures. A favorable combination of low internal stress, hardness, elasticity and high bonding strength produces coatings with exceptional resistance to wear and erosion. Only 1-3 μm coating of nanophase amorphic diamond could protect fragile substrates such as ZnS against erosive environments [1,2]. Nominal coatings with 75% diamond contents are produced with substrates rotated in the core of the laser plasma as shown schematically in Figure 1. The unique nodular structure of amorphic diamond films deposited by a core of laser plasma has been reported. Typically, the nodule size ranges from 10 to 50 nm in diameter and imparts the properties of diamond found in the finished films [1-2]. A typical appearance of an amorphic diamond obtained by the transmission electron microscopy (TEM) is reproduced in Figure 1.

The application of diamond and diamondlike carbon (DLC) films to electronic devices are of considerable interest and the advantage of heterojunction devices formed by combining a wide band-gap coating with a narrow band gap substrate is clear if the resistance of such coatings can be controlled [3]. Nanophase amorphic diamond films with nodules of diamond in a matrix of more conductive phases of carbon might offer a viable alternative [1,2]. Recent field emission measurements have demonstrated that these diamond coatings emit electrons at high current densities when immersed in modest electric field strengths and the electron emission could be adjusted by modifying the process parameters for the film production [4].

Deposition of thin films of nanophase amorphic diamond on Si and GaAs produces rectifying heterojunctions with highly asymmetric I-V characteristics and a reverse breakdown strength greater than 10^9 V/m as shown in Figure 2. Regardless of the doping type and its concentration in the substrate, current is rectified in the same direction with diamond layer acting as the cathode. The layered areas generate both current and voltage when illuminated acting as a source of photovoltaic power. When reversed biased, current levels from the heterojunction vary with the amount of reverse bias and the illumination. A photoconductive effect has been observed for these junction devices and current levels from the heterojunction vary with the amount of reverse bias and the illumination [5].

2 HIGH POWER APPLICATIONS

Our group at UTD has developed high power Blumlein pulsers that produce waveforms with pulse durations, risetimes and repetition rates in the range of 1-600 ns, 0.1-50 ns and 1-300 Hz, respectively, using a conventional thyratron, spark gap, or a high gain GaAs photoconductive semiconductor switch (PCSS). We have demonstrated several intense photoconductively-switched Blumlein pulsers that operate with a switch peak power in the range of 50-80 MW and activating laser pulse energies as low as 300 nJ [4]. Examinations of output waveforms have indicated durations in the range of 1-5 ns and risetimes as fast as 200 ps.

During the avalanche-mode photoconductive switching of the Blumlein pulsers, the current is concentrated in filaments that extend from the cathode to the anode across the insulating region of the PCSS. Carrier recombination results in the emission of characteristic band gap photons in the near infrared region, which can be seen by an infrared viewer. Filamentary currents with densities of several MA/cm^2 and diameters of 15-300 μm passing through a narrow channel can cause switch damage, especially at the contacts points. A greater number of filaments during each cycle of commutation reduce the stress on the switch, thereby increasing its lifetime.

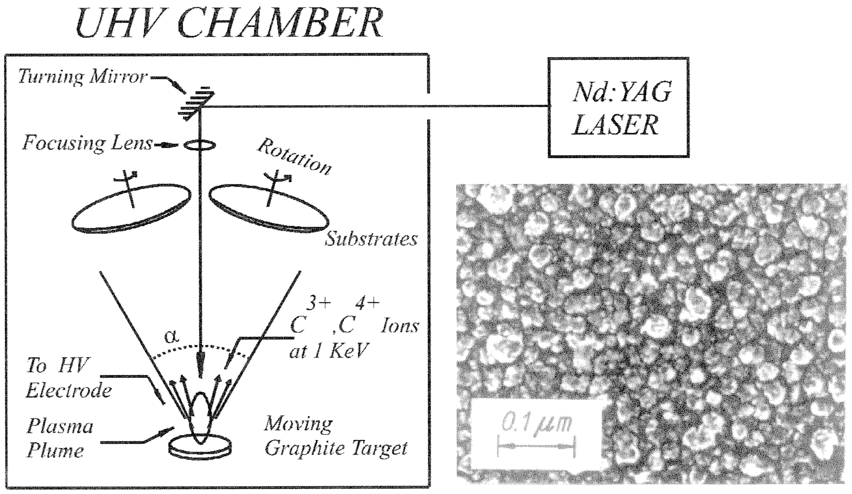

Figure 1: Schematic representation of the laser plasma discharge source used to prepare nanophase amorphic diamond coatings. Nano size nodules are seen in an image produced by TEM of a gold-coated replica of a film of amorphic diamond.

Our current research has been directed to study and implement the broadening of the current channels in the avalanche photoconductive switch in order to improve lifetime and increase switching peak power. The main approach is application of nanophase amorphic diamond coatings to the PCSS switch electrodes to enhance operation and lifetime in Blumlein pulse generators.

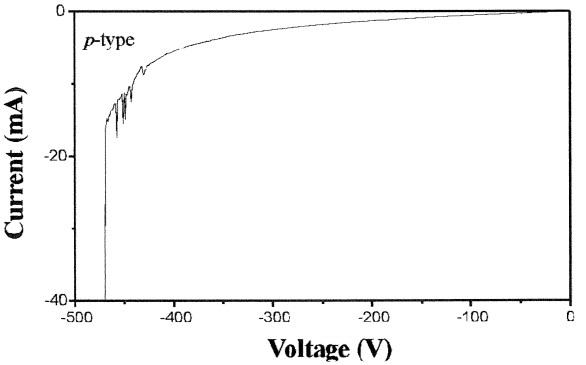

Figure 2: Current-Voltage characteristics showing the breakdown voltage for the nominal amorphic diamond film on p-type Si substrate. Measurements were performed in the dark under reverse bias conditions.

It is anticipated that, by depositing films of amorphic diamond near the switch contacts, the number of carriers and avalanche sites may increase aiding the switch performance. In addition, due to mechanical properties of amorphic diamond, damage to the switch at the contact points during commutation may be reduced, improving the switch lifetime. The initial concept for a diamond-coated PCSS is presented schematically in Figure 3. In this figure, the GaAs switch is shown with the metal electrode contacts and a coating of amorphic diamond on and around the cathode electrode.

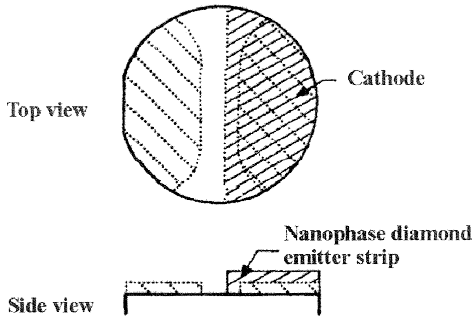

Figure 3: Schematic diagram of the concept for a GaAs PCSS with pre-avalanche seeding from amorphic diamond.

3 DIAMOND-TREATED SWITCH PERFORMANCE AND LIFETIME

In this work, nanophase amorphic diamond coatings were deposited on one side of semi-insulating liquid encapsulated Czochralski (LEC) grown GaAs substrates with resistivity of about 1.0×10^7 Ω cm, the type used in our Blumlein pulsers as the photoconductive switch material. Electrode copper foils were attached to either side using conducting silver paint and epoxy. Electrodes were attached to opposite sides of the switch, and conduction was through bulk of the GaAs, with the switch gap setting of 5 mm. A Keithley 237 high voltage source-measure unit was used to provide constant voltage bias while monitoring the current through the sample. For measurements of forward diode characteristics, diamond coating was biased negative with respect to the substrate.

Typical current-voltage characteristics measured for 0.5-μm and 1.0-μm nominal amorphic diamond films on semi-insulating GaAs are shown in Figure 4. For comparison, the I-V plot for an uncoated similar GaAs substrate is included in this figure. The rectifying behavior for the coated samples seen in Figure 4 was attributed to the amorphic diamond/GaAs heterojunction because the I-V plot for the uncoated sample showed symmetrical and ohmic character with change in the voltage polarity. The I-V characteristics differ considerably for the diamond sample, especially for the forward current region where the coating side was biased negative.

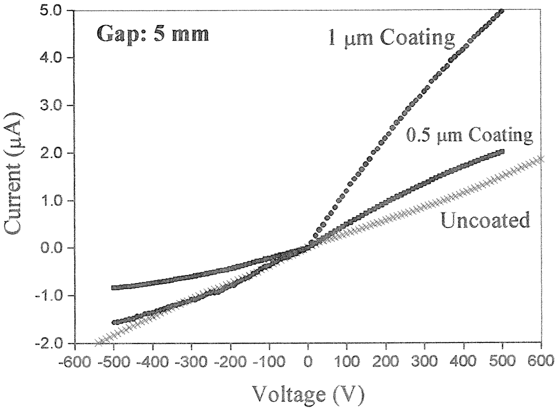

Figure 4: Current-voltage characteristics measured in the dark for an uncoated sample and two samples of diamond-coated GaAs switch substrate with a gap setting of 5 mm.

The rapid current increase in the forward direction for the coated sample has been attributed to tunneling of electrons from amorphic diamond to the conduction band of GaAs, a process similar to Fowler-Nordheim tunneling [4]. As seen in Figure 4, the 1.0-μm diamond coating enhances the current increase in the forward direction when compared to the sample with a 0.5-μm coating. The tunneling of electrons from amorphic diamond to the conduction band of the GaAs provides pre-avalanche sites for the operation of diamond-coated PCSS, and thereby diffuses the conduction current. The rectifying character under reverse bias is clearly seen in Figure 4 for both coated samples, with the thicker film reducing the process of rectification.

The switch/electrode configuration used in the PCSS lifetime studies is a part of a low profile switch assembly [4] that facilitates the use of a single photoconductive switch in the pulser. The electrode assembly allows for operation of PCSS in either lateral or opposed configurations. Each switch was fabricated from one half of a semi-insulating LEC grown GaAs wafer with a diameter and thickness of 5 cm and 0.5 mm, respectively. It was held in place by means of two copper holders screwed to the electrodes. Commutation of the switch was triggered at 905 nm by focusing the LD-220 laser diode array beam in two straight lines across the switch gap.

Improvements in the PCSS switch operation and lifetime have been examined in a lateral configuration by coating the triggered face of GaAs switch cathodes with strips of highly adhesive films of amorphic diamond. With the application of amorphic diamond, not only the switch lifetime was increased, but also the damage at the cathode contact was found to be less than that found for the anode contact [4]. This indicated that the diamond coating protected and hardened the cathode side.

In this work, we studied the lifetime of three GaAs switches with a 1-cm strip of 0.5-μm diamond coatings deposited on the switch at electrode locations: cathode, or anode, and/or both cathode and anode. All switches were installed in an opposed configuration where the electrodes were attached to opposite sides of switch and conduction was through the bulk of GaAs. A switch gap of 5 mm was chosen for this study. The switch was tested at 18 MW (0.6 kA and 30 kV) until they failed. Under similar conditions of experiments and switch configuration, we performed a switch longevity experiment with an uncoated GaAs switch. Results of these studies are given in Table 1. Test results indicate significant switch lifetime improvement by the application of amorphic diamond.

The schematic drawing of the switch damage for the test condition where diamond films deposited on both anode and cathode electrodes is presented in Figure 5. The switch gap is shown by the two horizontal lines of damage located at the front and the back of the switch corresponding to the limit of the copper plate electrodes. For comparison the negative photographs of the switch electrode areas after 10^4 shots are also shown in Figure 5. The appearance of damage is consistent with the results of the switch lifetime tests presented in Table 1. It appears that the damage at the electrode contact areas eventually caused thermal runaway at the switch gap surface and produced a crack that shorted the gap. In experiments where the switch had no diamond coating, the majority of the time, a single current filament commutated the switches. The filament was initiated near the cathode and followed, approximately, one of the laser beams to the anode. Multiple branching was rarely seen [4]. In the case of the switch with diamond coating, the multiple branching was observed more often, indicating an increase of pre-avalanche sites.

Test Condition	**Switch Lifetime**
Uncoated Switch	1 x 10^4 pulses
Diamond coating at anode	4 x 10^4 pulses
Diamond coating at cathode	1 x 10^5 pulses
Diamond coatings at both anode and cathode	3 x 10^5 pulses

Table 1: Results of switch longevity tests.

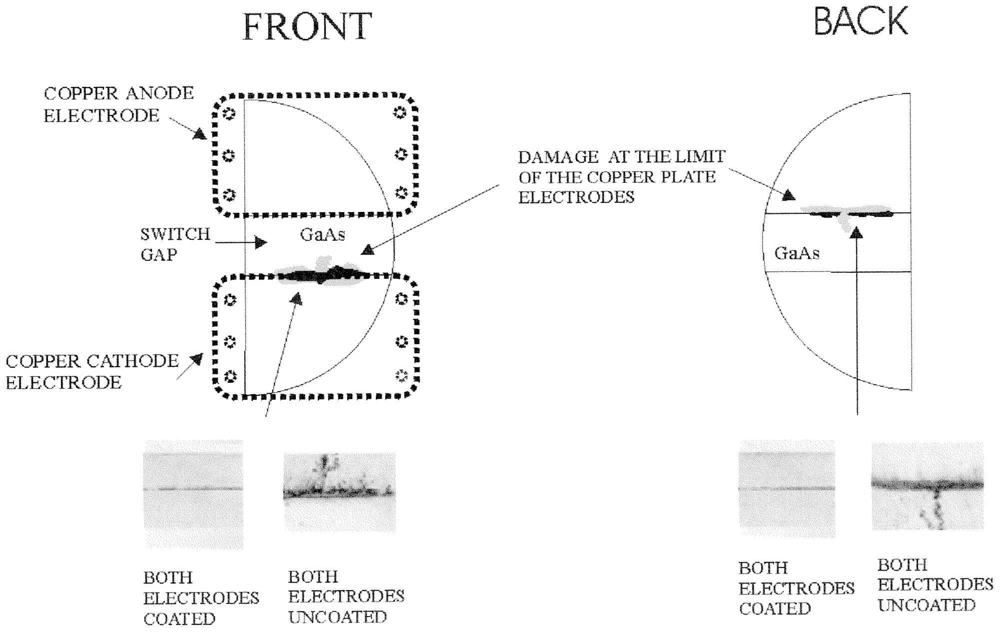

Figure 5: Schematic drawing of the appearance of damage on both sides of switch used in these studies. For comparison the negative photographs of the switch electrode areas for coated and uncoated switches are shown after 10^4 commutation cycles.

Enhancing or restricting the current conduction flow at the interface between amorphic diamond and PCSS material has pronounced effect upon the off-state switch hold-off and switch performance. For example, the tunneling of electrons from amorphic diamond to GaAs during the off-state stage of PCSS operation provides pre-avalanche sites that may diffuse conduction current upon switch activation. However, this may also increase leakage current at high fields causing switch shorting and failure. To avoid such problems for a particular charging voltage, it may be necessary to limit the current injection by controlling the switch gap, diamond film thickness and the laser diode beam delivery to the switch.

In this work, the diamond coating of the switch anode area has resulted in longer switch lifetime as indicated in Table 1. In this case the amorphic diamond inhibits the flow of electrons at the interface until very high fields are reached. This is due to rectifying behavior of the amorphic diamond/GaAs heterojunction operating under reverse bias condition as discussed earlier in this report.

The semiconductor properties of amorphic diamond described earlier have been employed to improve the PCSS longevity by coating the switch cathode or anode areas or both. However, the critical issue to resolve is the switch design options that make optimal use of nanophase amorphic diamond coatings for long-life operations of avalanche PCSS in high power pulsers. Design options include: switch configuration, switch gap setting, diamond film thickness, exact locations of diamond coatings and film qualities.

ACKNOWLEDGMENTS

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