Design, Fabrication and Performance of a Diamond Treated High Power Photoconductive Switch

Farzin Davanloo*, Carl B. Collins*, and Forrest J. Agee+

*Center for Quantum Electronics, University of Texas at Dallas, P.O. Box 830688, Richardson, TX 75083-0688

Abstract. In this work, the semiconductor properties of amorphous diamond have been employed to improve the GaAs photoconductive semiconductor switch longevity by coating the switch cathode or anode areas or both. If the switch cathode is coated, the tunneling of electrons from amorphous diamond to GaAs during the off-state stage of PCSS operation provides pre-avalanche sites that diffuse conduction current upon switch activation. On the other hand, diamond coating of the switch anode results in increased hold-off characteristics and longer switch lifetimes by blocking the leakage current. In this case the rectifying behavior of the amorphic diamond/GaAs heterojunction operating under reverse bias condition restricts the conduction until very high fields are reached.

INTRODUCTION

The Blumlein pulsers developed at the University of Texas at Dallas (UTD) have produced high power 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 photoconductive switch. These pulsers have been extensively characterized and their versatility has been demonstrated [1].

Our recent efforts have resulted in demonstration of several intense photoconductive-switched Blumlein pulsers. Presently, these devices operate with a switch peak power in the range of 50-80 MW and activating laser pulse energies as low as 300 nJ [2]. Examinations of output waveforms have indicated pulse durations in the range of 1-5 ns and risetimes as fast as 200 ps. Table 1 present the best simultaneous and individual results obtained, to date, by switching the stacked Blumlein pulsers with a high gain GaAs photoconductive semiconductor switch (PCSS).

SWITCH DESIGN CONSIDERATIONS

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/cm² 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.

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 amorphic diamond coatings to the PCSS switch electrodes to enhance operation and lifetime in Blumlein pulse generators.

Basic research in our laboratory has developed a conformal coating that has the hardness of natural diamond and exceptionally high values of electron emissivity. This material has been termed amorphous ceramic diamond and later shortened to "amorphic diamond" for convenience. Deposited at room temperatures it forms a strong bond to any material onto which it is applied. Such a favorable combination of hardness, chemical bonding and elasticity should translate directly into an increased resistance to abrasive wear of components coated with amorphic diamond. It has been demonstrated that only a 1-3 µm coating of amorphic diamond could protect fragile substrates against erosive environments [3,4].
TABLE 1. Best simultaneous and individual test results obtained by commutation of 2-line stacked Blumlein pulsers with the high gain GaAs switches.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Simultaneous Results</th>
<th>Individual Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch Voltage</td>
<td>60 kV</td>
<td>30 kV</td>
</tr>
<tr>
<td>Switch Current</td>
<td>1.2 kA</td>
<td>0.6 kA</td>
</tr>
<tr>
<td>Pulse Risetime</td>
<td>200 ps</td>
<td>200 ps</td>
</tr>
<tr>
<td>R-M-S Jitter</td>
<td>500 ps</td>
<td>500 ps</td>
</tr>
<tr>
<td>Optical Trigger Energy</td>
<td>300 nJ</td>
<td>300 nJ</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Electric Field</td>
<td>60 kV/cm</td>
<td>60 kV/cm</td>
</tr>
<tr>
<td>Stack Voltage</td>
<td>112 kV</td>
<td>57 kV</td>
</tr>
<tr>
<td>Switch Lifetime</td>
<td>$1 \times 10^6$ pulses</td>
<td>$3 \times 10^6$ pulses</td>
</tr>
</tbody>
</table>

Analytical techniques have shown amorphic diamond to consist of nodules of tens of nanometers in diameter that are composed of sp3 (diamond) bonded carbon in a matrix of other carbons. The diamond character has been confirmed by the agreement of structural morphology, density, optical properties, Kα line energies and hardness. The nodules seem to be disordered mixtures of the cubic and the rare hexagonal polytypes of diamond that have no extensive crystalline planes along which to fracture. Since it is condensed from laser plasmas produced under conditions that are also optimal for the growth of interfacial layers, the films of amorphic diamond are strongly bonded to the substrates onto which they are condensed [3,4].

It has been determined that amorphic diamond emits electrons at high current densities when immersed in modest electric field strengths [5]. It is, therefore, 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 Fig. 1. 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.

**DIAMOND-COATED SWITCH BEHAVIOR**

In this work, amorphic diamond coatings were deposited on one side of semi-insulating liquid encapsulated Czochralski (LEC) grown GaAs substrates with resistivity of about $1.0 \times 10^7 \Omega$ 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 in the range 0-600 V while monitoring the current through the sample. For measurements of forward diode characteristics, diamond coating was biased negative with respect to the substrate.

![Top view](image1)

**FIGURE 1.** Schematic diagram of the initial concept for a GaAs PCSS with pre-avalanche seeding from amorphic diamond.

Typical current-voltage characteristics measured for 0.5-µm and 1.0-µm nominal amorphic diamond films on semi-insulating GaAs are shown in Fig. 2. 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 Fig. 2 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.

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 [5]. As seen in Fig. 2, 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 rectifying character under reverse bias is clearly seen for both coated samples, with the thicker film reducing the process of rectification.

Of importance to our studies, is the rapid current increase in the forward direction as seen in Fig. 2. 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.

**SWITCH PERFORMANCE AND LIFETIME**

The switch/electrode configuration used in the PCSS lifetime studies is a part of a low profile switch assembly [1,5] 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 from cathode to anode.

![Figure 2](image)

**FIGURE 2.** 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.

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 [5]. 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 2. Test results indicate significant switch lifetime improvement by the application of amorphic diamond.

The schematic drawing of the switch damage for the test conditions of Table 2 is presented in Fig. 3. 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 Fig. 3. The appearance of damage is consistent with the results of the switch lifetime tests presented in Table 2. 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 [1]. In the case of the switch with diamond coating, the multiple branching was observed more often, indicating an increase of pre-avalanche sites.

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Switch Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated Switch</td>
<td>$1 \times 10^4$ pulses</td>
</tr>
<tr>
<td>Diamond coating at anode</td>
<td>$4 \times 10^5$ pulses</td>
</tr>
<tr>
<td>Diamond coating at cathode</td>
<td>$1 \times 10^7$ pulses</td>
</tr>
<tr>
<td>Diamond coatings at both anode and cathode</td>
<td>$3 \times 10^5$ pulses</td>
</tr>
</tbody>
</table>
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.

As indicated in Table 2, the diamond coating of the switch anode area has resulted in increased hold-off characteristics of the PCSS in the off-state stage of operation leading to longer switch lifetimes. 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 amorphic diamond coatings for long-life operations of avalanche PCSS in stacked Blumlein pulsers. Design options include: switch configuration, switch gap setting, diamond film thickness, exact locations of diamond coatings and film qualities.

ACKNOWLEDGMENTS

This work was supported by the Air Force Office of Scientific Research (AFOSR) under Grant F49620-00-1-0296.

REFERENCES