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DIAMOND SWITCHES FOR HIGH TEMPERATURE ELECTRONICS*

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ABSTRACT

This paper presents the results of switching voltages of 500 V and currents of 10 A using chemical vapor deposited (CVD) diamond as a switching material. The switching is performed by using an electron beam that penetrates the diamond, creates electron hole pairs, and lowers its resistivity to about 20 Ω-cm and its resistance to about 4 Ω. Tests were performed at room temperature but in a configuration that allows for 250 C.

INTRODUCTION

Diamond is being studied as a switch material for high temperature applications [Joshi et al, 1993; Lin et al, 1993; Schoenbach et al, 1992; and Prasad et al, 1996]. The material properties of diamond for high voltage and high temperature far surpass those of silicon (and most other semiconductors). Most notably, the electric field breakdown strength of diamond is >30 times that of silicon, the thermal conductivity of diamond is >10 times that of silicon, and the maximum operating temperature is >700 C for diamond compared with <200 C for silicon [Plano et al, 1993].

Electron beam controlled diamond switches have been demonstrated using either natural type IIa diamond crystals or chemical vapor deposition (CVD) grown diamond films. Different modes of diamond switch operation have been observed depending on how deep the e-beam is injected into the diamond and the type of electrical contact that is used [Joshi et al, 1993; Schoenbach et al, 1992]. These experiments were done at modest voltages and electric fields, well below the breakdown strength of the diamond. A short summary of this work is presented below since it lays the foundation for our work. The different modes of switch operation are: fully penetrating e-beam switching mode, single injection mode and double injection mode.

Fully Penetrating Electron-Beam Switching Mode

In its simplest form, the e-beam controlled diamond switch consists of a thin slab of diamond to which blocking (Schottky barrier) electrical connections have been made. In its natural state diamond is an insulator so no current will flow when a voltage is applied across the diamond. To turn the switch on, an electron beam is injected through one of the electrodes and into the diamond to the full depth of the diamond slab. As the energetic e-beam deposits energy in the diamond, it generates electron-hole pairs, reducing the resistivity of the diamond and allowing current to flow. Each energetic electron makes multiple charge carriers, one electron-hole pair per 15 eV of electron energy. This provides a charge and current gain of 10^4 for a 150 keV e-beam. In this mode of operation the diamond can be

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no thicker than an electron range if the whole switch volume is to be filled with charge carriers.

Single and Double Injection Mode

If one (single injection) or both (double injection) electrical contacts are made to allow for charge injection at the electrode, the switch will operate in a space charge limited regime [Lampert, 1970]. For the double injection approach the current density, J, carried by the switch is given by:

$$J = \varepsilon \, \mu_n \, \mu_p \, \tau \, (V^3/d^5) \tag{1}$$

where μ_n and μ_p are the electron and hole mobility, ε is the dielectric constant of the diamond, and τ is the charge carrier life-time. Here V is the on-state voltage and d is the thickness of the diamond. For operation in either single or double injection mode, the switch is turned on with a lower energy electron beam (55-70 keV) that stops in the region near the electrical contact. The double injection mode proved the best operating regime in the experiments reported by Joshi et al (1993). Current densities >5 kA/cm^2 were conducted with 25 V forward voltage across the switch when switched with a 6 mA/cm^2, 55 keV e-beam. Particularly intriguing from the point of view of high voltage switching was that current densities observed in the experiment were far in excess of what Eq. 1 would predict. Joshi et al (1993) speculate that in the high current density regime, trap filling quickly occurs which then substantially increases the carrier life time.

The rest of this paper is arranged as follows: Section 2 describes the experimental apparatus used and some tests of the diamond at elevated temperatures. Section 3 describes the results of the electron beam experiments on natural and CVD grown diamond and discusses their implications.

EXPERIMENTAL SETUP AND INITIAL HIGH TEMPERATURE TESTS

Figure 1 shows a schematic diagram of the diamond switch and the electron gun being used for the demonstration experiments. We plan to demonstrate high temperature switching in diamond by elevating the temperature of the diamond switch to 250 C. In order to heat the diamond to 250 C, it is only necessary to heat the diamond mount (shown in figure 2). The electron beam diode and the vacuum chamber can be held at much lower temperatures. The diamond mount is composed of a ceramic mount, metallization deposited on the diamond, and solder (at the bottom of the diamond) or wires (at the top) to make contact to the rest of the electrical circuit. For the success of the demonstration it must be shown that each of the switch components operates at 250 C.

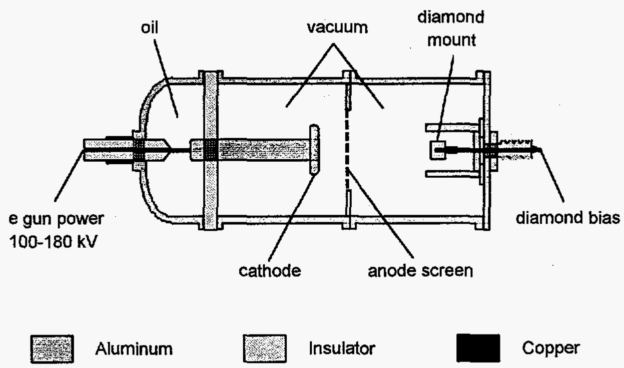


Figure 1: Schematic diagram of the electron gun and diamond switch mount.

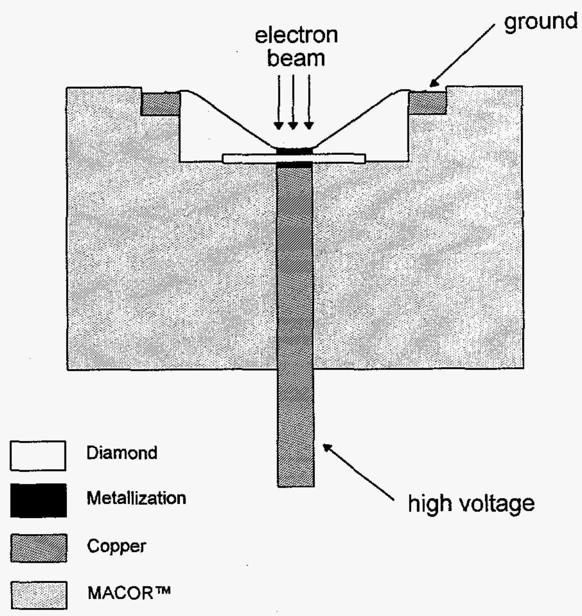


Figure 2: Diamond switch mount, including a ceramic holder, metallization on the diamond, solder, and wire bonding.

The ceramic in the mount is capable of withstanding temperatures as high as 1000 C. The copper rod that connects the diamond to the high voltage bias can be taken to close to its melting point. What are at issue are the wire bonds from the diamond to the ground of the external circuit, the metallic contacts deposited on the diamond, and the diamond itself. The issue with the diamond itself is the leakage current through the diamond as a function of temperature. In order to test these sub-systems, a ceramic mount was fabricated to place the diamond and its metallized contacts in a 300 C oven. Figure 3 shows a schematic diagram of this holder.

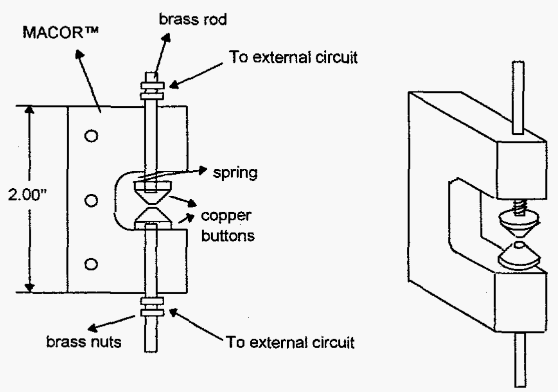


Figure 3: Schematic diagram showing a holder made from MACOR to test the I-V characteristics of the diamond at high temperature.

The diamond (a 5 mm diameter, 100 μm thick, natural Type IIa diamond) was clamped between the two copper buttons. The brass rods were connected to a power supply, current limiting resistor, a voltmeter and an ammeter. The entire holder was placed in an oven and the temperature was raised to 300 C. The I-V characteristics of the diamond, under dc bias, were measured first at room temperature and then again at 300 C. The leakage current at room temperature was below the lowest measurable (~2 nA) at bias voltages as high as 1000 V dc. Figure 4 shows the I-V characteristics at 300 C. Even at this elevated temperature the leakage current was 35 nA at even the highest bias voltages. This produces a negligible loss in a switch that will be conducting ~100 A. At this time it is not known why the I-V characteristics are different for different bias polarity. We are investigating this phenomenon.

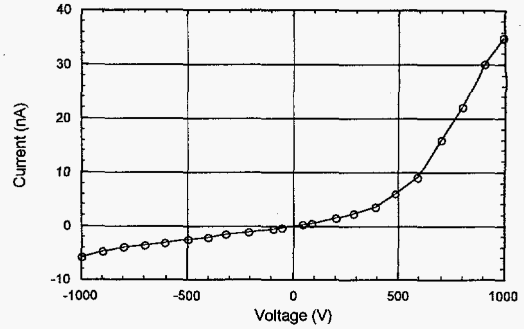


Figure 4: Diamond I-V characteristics under dc bias at 300 C.

The metal contacts deposited on the diamond were examined under a microscope after this test. No detachment or visible change was seen. Finally, the diamond was suspended within the oven by means of the foil bonds to determine if the bonds weaken after exposure to elevated temperatures. Raising the temperature to 300 C in air had no impact on the foil bonds.

We are now performing switching experiments at elevated temperatures. One point of concern is the solder contact between the diamond and the copper rod (see Figure 2). For this we will use a Au-Ge solder that has a 360 C melt point.

ELECTRON BEAM SWITCHING OF CVD GROWN AND NATURAL DIAMOND

Recent work on the growth of CVD diamond films has demonstrated that it is practical to grow large area, high quality films with electronic properties (carrier mobility and lifetime) as good as natural type IIa diamond. [Plano et al, 1993] This advance has opened the possibility of large area, extremely high power diamond switches at a reasonable cost.

In our experiments, we have controlled high voltages using electron beam switching of natural type IIa diamond and CVD diamond at room temperature. The data for the natural diamond were previously presented [Prasad et al, 1996]. The CVD diamond tested was a 10 mm by 10 mm, 100 μm thick optical grade with 2.5 mm diameter metallization. The natural diamond used was also 100 μm thick. The same electron gun was used for both diamond samples. The diamond is biased using a 0.3 μF capacitor which is in series with a 49 Ω load (Figure 5). The conduction current is measured by a Pearson transformer, while the on-state voltage is measured by an uncompensated resistive voltage divider that is connected to the diamond via a blocking capacitor as shown. An important aspect of this work is to make certain that the electron beam does not impact the totality of the surface area of the diamond. To limit the triggering electron beam we use a limiting aperture placed over the upper ground plane that restricts the diameter of the electron beam that impacts the surface of the diamond to an area slightly larger than the metallized area. This aperture is not shown in figure 2.

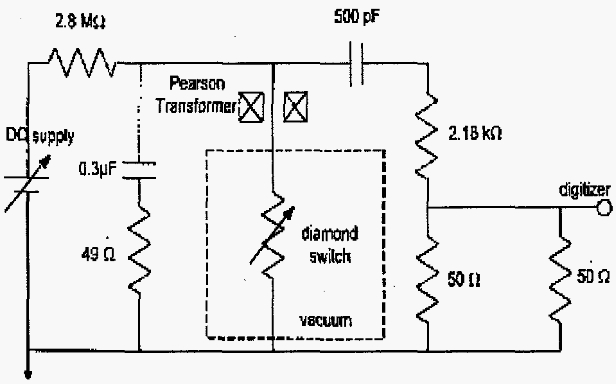


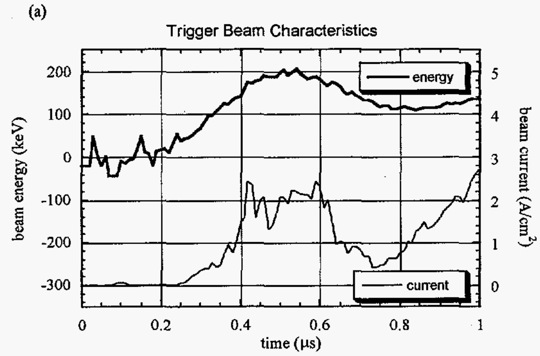
Figure 5: Circuit used to measure the on-state resistivity of natural and CVD diamonds.

The bias (negative) is applied to the lower face of the diamond (through the copper rod shown in Figure 2) by the 0.3μF capacitor. When the diamond conducts, the capacitor charge decays on a time-scale of 49 Ω x 0.3μF = ~15μs. This time scale is long compared to the typical 0.2 μs duration of the trigger e-beam, so the bias is essentially constant during the conduction. Figure 6 shows data from the CVD diamond test.

Figure 6(a) shows the electron beam energy and current. The beam energy is the voltage at the diode used to generate the beam. In these experiments a carbon fiber cathode was used to generate the electron beam. The beam current is measured using an annular Faraday cup around the aperture that is used to expose the diamond switch to the electron beam.

Figure 6(b) shows the diamond switching data. A simple bias circuit like the one used with natural diamond and described by Prasad et al (1996) was used. The 50 Ω external resistor in the circuit and the initial capacitor voltage of 500 V limit the current to 10 A. The measured current and voltage across the diamond lead to the determination of the diamond on-state resistance and hence resistivity since the diamond thickness and active area are known. The noise in the measurement of the current and voltage contribute to the noise in the resistivity, leading to what appears to be a negative resistance. Obviously, this is not the case. We are presently working to limit this noise to obtain cleaner data.

(a)



(b)

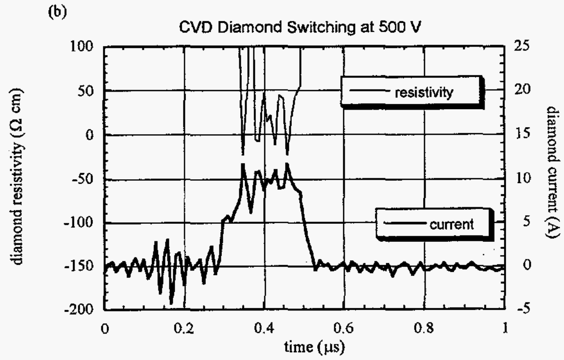


Figure 6: Data from CVD diamond switching experiment. (a) Electron beam energy and current. (b) Conduction current within the diamond and diamond on-state resistivity.

Over the ~0.2 μs of conduction (concurrent with the presence of the electron beam) the average resistivity is very low: 20 Ω-cm. This number is similar to that measured using natural type IIa diamond. This is a significant result. Consider the impact on a practical 300 V/100 A switch. Using similar current densities as measured in this experiment (10 A in a 2.5 mm diameter spot or 200 A/cm^2), a 100 A switch will require an 8 mm diameter active area. These data were taken at 500 V with a 100 μm thick diamond resulting in an average field of 50 kV/cm. Assuming that we can use fields of 300 kV/cm, a 300 V switch would imply a 10 μm thick diamond. With these numbers, the resistivity of 20 Ω-cm translates to an on-state resistance of 0.04 Ω. For 100 A conduction current at 300 V this implies a 4 V on-state voltage. This is a very efficient switch. Work needs to be done to optimize the electron beam to reduce losses in the trigger and obtaining thinner diamonds.

FUTURE PLANS AND CONCLUSION

We have shown that it is feasible to switch high voltages (500 V), and current density (200 A/cm^2) by switching CVD grown diamond using electron beams. The diamond's resistivity, during switching, is about 20 Ω-cm and its resistance is about 4 Ω. Tests were performed at room temperature but in a configuration that allows for 250 C. Future plans call for a demonstration of switching at this temperature with both natural diamond and CVD grown diamond.

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