SAND96-1067C
CONF-9606159--2
Report #aasc96TM-13

DIAMOND SWITCHES FOR HIGH TEMPERATURE ELECTRONICS

Rahul R. Prasad, Gary Rondeau, Niansheng Qi and Mahadevan Krishnan
Alameda Applied Sciences Corporation
1555 Doolittle Drive, Suite 100
San Leandro, CA 94577
Tel. (510) 483-4156

Guillermo M. Loubriel, Fred J. Zutavern, Mitchell H. Ruebush
and Wesley D. Helgeson
Sandia National Laboratories
1515 Eubank Street SE
Albuquerque, NM 87185-1153
Tel. (505) 845-7096

prepared for

Third International High Temperature Electronics Conference
Albuquerque, NM

April 25, 1996

All correspondence regarding this manuscript to be sent to:
Dr. Rahul R. Prasad
Alameda Applied Sciences Corporation
1555 Doolittle Drive, Suite 100
San Leandro, CA 94577.

DISCLAIMER

DISCLAIMER

DIAMOND SWITCHES FOR HIGH TEMPERATURE ELECTRONICS

Rahul R. Prasad, Gary Rondeau, Niansheng Qi and Mahadevan Krishnan
Alameda Applied Sciences Corporation
1555 Doolittle Drive, Suite 100, San Leandro, CA 94577
Tel. (510) 483-4156

Guillermo M. Loubriel, Fred J. Zutavern, Mitchell H. Ruebush, and Wesley D. Helgeson
Sandia National Laboratories
1515 Eubank Street SE, Albuquerque, NM 87185-1153
Tel. (505) 845-7096

Abstract

Diamond switches are well suited for use in high temperature electronics. Laboratory feasibility of diamond switching at 1 kV and 18 A was demonstrated. DC blocking voltages up to 1 kV were demonstrated. A 50 Ω load line was switched using a diamond switch, with switch on-state resistivity ≈7 Ω-cm. An electron beam, ≈150 keV energy, ≈2 μs full width at half maximum was used to control the 5 mm x 5 mm x 100 μm thick diamond switch. The conduction current temporal history mimics that of the electron beam. These data were taken at room temperature.

1. INTRODUCTION

Diamond switches are particularly well suited for high voltage, high current switching in high temperature, close-packed, high acceleration conditions that are typical of modern and future aircraft designs. Diamond's advantage over semiconductor switches lies in its large bandgap (5.5 eV) which reduces the conductivity at high temperatures. A 300 V/ 250 A (75 kW) switch should encompass different applications of switches for the More Electric Aircraft (MEA). An example of such an application is driving switched reluctance motors for electric actuators. Other applications for diamond switches are: power controllers, power switches, radar systems, and in the Integral Starter Generator (ISG) and the Internal Power Unit (IPU) of the MEA. More advanced applications require a 1000 V/100 A switch. Outside the realm of the MEA, other DoD applications are for the Electric Tank, Electric High Mobility Multipurpose Wheeled Vehicle (HMMWV or Humvee) and in BMDO's ground based radar. Sandia National Laboratories is interested in studying these switches for possible application in DOE's Accelerator Produced Tritium project. This technology is dual-use since switches that operate at temperatures above 200 °C are required in automobiles, drilling rigs, high voltage pulsed laser power supplies, the power distribution industry, and high power accelerators.

Alameda Applied Sciences Corporation (AASC) was awarded a Phase I STTR contract by the US Air Force, Wright Labs. The primary objective of the Phase I effort was to demonstrate electron-beam controlled switching in natural diamond at voltages up to 1000 V with forward conduction currents of up to 10 A. The on-state voltage of the switch was also to be measured. During the course of this Phase I effort, AASC, with its partner, Sandia National Laboratories (SNL) demonstrated switching with 1000 V dc hold-off, forward conduction currents of ≈18 A and on-state switch resistivities of ≈7 Ω-cm. These operating parameters demonstrate the feasibility of an efficient diamond switch capable of operating at blocking voltages in excess of 1000 V, conducting currents up to 1000 A with on-state voltage drop across the switch as low as 1-4 V.

A high temperature, compact and efficient diamond switch for 1000 V/1000 A operation, for example, is envisioned to use a 4 cm^2, 10 μm thick, CVD diamond with a 2 cm^2 active area. Using a ≈40 keV electron beam to control the switch, the on-state voltage drop is expected to be ≈2 V. The switch is expected to be capable of operation at elevated temperatures, up to 400 °C, with no degradation of performance. This switch is bi-directional, unlike semiconducting junction switches. Conduction current is maintained as long as the control electron beam is incident on the switch. The switch starts/ceases conduction with the turn-on/turn-off of the electron beam in the time it takes to sweep the electron beam on and off the diamond. There is no intrinsic delay within the diamond that increases the turn-on and turn-off time of these switches.

The rest of this paper is arranged as follows: Section 2 describes the experimental apparatus used. Section 3 reviews the literature on electron beam controlled diamond switching. It also discusses the expected results using an empirical model. Section 4 describes the results of the experiments. Section 5 discusses their implications.

2. EXPERIMENT

The experiments described in this paper utilize an electron beam to trigger the switch. The electron beam system is capable of delivering a beam with currents in excess of 10 A/cm^2 with electron beam energies up to 150 keV. The beam pulse length is about 1.5 µs. Figure 1 shows a schematic diagram of the electron beam system. It also shows the location and details of the mounting of the diamond switch. The electron beam is generated using a velvet covered cathode that is 5" in diameter and is located 2 cm upstream of a metallic mesh anode. The parameters of the electron gun used in these experiments were not optimized.

The switch is mounted about 8" downstream of the anode in the electron beam vacuum chamber. A 5 mm x 5 mm x 100 µm thick diamond sample was used for these experiments. This sample had 2 mm diameter metallic contacts, both being 600 Å Ti, 1200 Å Pt and 1 µm Au. It was connected to the external circuit (shown in Figure 2) on the ground side using silver epoxy. The other electrode was connected to the high voltage side of the circuit using six ribbon bonds. The resistance of this sample at a 1 kV bias was about 10^{12} Ω.

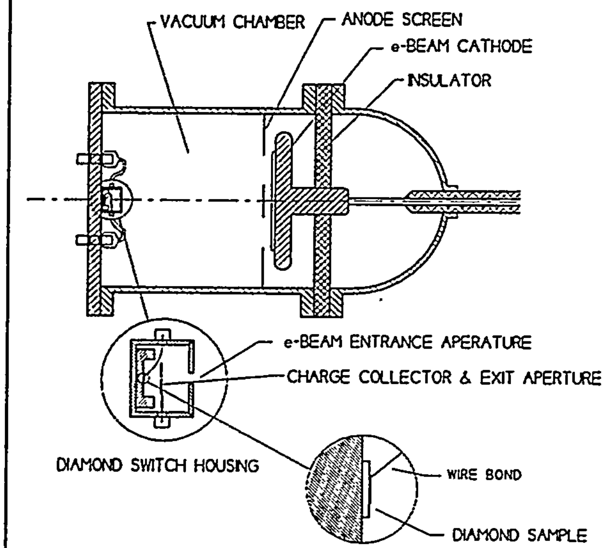

Figure 1: Schematic diagram of the electron beam apparatus and the mounting of the diamond switch.

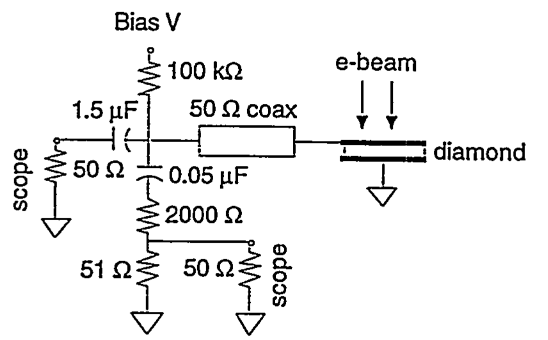

Figure 2: Circuit used to demonstrate switching.

As seen in Figure 1 a disc is used to cover the diamond switch. The aperture in this disc is 2 mm in diameter to allow the electrons to impinge only on the metalization on the diamond face. This disc also serves as a Faraday cup to measure the electron beam current that is incident on the switch. Additionally, the disc shields the unmetalized parts of the diamond from the beam reducing the risk of surface flashover. The disc Faraday cup and diamond switch are further shielded by the grounded enclosure (Fig. 1).

The circuit used in the switching experiments is shown in Figure 2. The diamond is biased using a 1.5 µF capacitor through a 50 Ω coaxial cable. The current switched through the diamond is measured using the voltage developed across the 50 Ω input of the digitizer. The voltage at the diamond switch is measured using the capacitively coupled 81:1 voltage divider shown. Additionally, the electron beam current incident on the diamond was measured (in some of the experiments) using the annular Faraday cup located upstream of the diamond and coaxial with the circular metal contacts on the diamond.

3. LITERATURE REVIEW AND EXPECTED RESULTS

One of the earliest reported experiments demonstrating electron bombardment induced conductivity was reported by McKay.[1] A sample of natural type II diamond, 6.3 mm in diameter and 0.45 mm thick, biased at up to 1000 V (22 kV/cm) was irradiated with 14 keV electrons. Current gains (defined as ratio of the forward current to electron beam current) up to 600 were measured.

Both natural type IIa and CVD diamond films grown on silicon substrates have been used in more recent experiments with electron beam triggering. [2-4] The quality of the CVD used [4] was not very good. The electron and hole mobilities were an order of magnitude lower than those of natural diamond and the carrier lifetimes were an order of magnitude lower. However, it is important to note that the CVD diamond samples were able to withstand electric field stresses up to 1.8 MV/cm. Recent advances in CVD manufacture remove the carrier mobility and lifetime constraints and make CVD diamond just as suitable as natural diamond for switching purposes. In particular, AASC comparisons of natural and electronic grade CVD diamond for use as x-ray photodetectors show that the two types of diamond have very similar sensitivity and temporal response to the incident x-ray pulses.

Lin et. al [3] used several samples of different cross sectional areas and thickness including a 3 mm diameter, 12 μm thick natural type IIa diamond and a 4.2 mm x 6.7 mm x 25 μm thick natural type IIa diamond with Ohmic contacts for switching experiments. Ohmic contact metalization consisted of a 2 mm diameter disk of 600 Å Ti, 1200 Å Pt overcoated with 2000 Å Au on the side facing the e-beam and a 3 mm diameter disk of 600 Å Ti, 1200 Å Pt overcoated with ≈1 μm Au on the reverse side. The diamond samples were dc biased at fields up to 250 kV/cm with no evidence of breakdown. The on-state voltage and forward current were not reported. However, an experiment on a 10 μm thick diamond bombarded with a 55 keV e-beam showing a current gain of 1900 was reported.

Experiments at Lawrence Livermore National Laboratory (LLNL) and Old Dominion University using natural type IIa [2] and CVD diamond [4] have been reported in the literature. The natural diamond experiments used 35 μm and 50 μm thick diamond samples irradiated with electron beams with energies ranging from 55 keV to 137 keV. The electron beam pulses ranged from 1 - 15 μs in pulse duration and had peak currents up to 35 mA/ cm^2. Blocking voltages up to ≈1200 V were demonstrated using the three types of electrode geometries. Switch forward current densities ranging from a few A/cm^2 to as high as ≈5 kA/cm^2 were demonstrated. Current gains (ratio of the forward current to the electron beam current) ranging from ~10^4 to ~10^6 were also measured. On-state voltages around 18 V were measured. However, it is not clear if this is the lowest on-state voltage that was measured. If this indeed were the lowest on-state voltage, it is not clear from the reported work what factors limited the on-state voltage.

One of the electrode configurations studied was the double injecting contacts configuration. In this configuration the switch is forward biased, with the electron beam irradiated face being biased positively. The contact opposite the electron irradiated face acts as an electron source while the electron beam generates electron-hole pairs in the volume near the irradiated contact, allowing for higher current and power gains than in the single injecting or blocking configurations. The resultant switch current density [2] is:

$$J_d = \varepsilon_r \varepsilon_o \mu_n \mu_p \tau \left(V^3 / d^5\right), \tag{1}$$

where μ_n and μ_p are the electron and hole mobilities, and τ is the charge carrier lifetime.

The current density is proportional to the cube of the forward voltage. In fact, the 50 μm thick diamond supports as much current as is expected from Eq. (1) for a 10 μm thick sample. The authors [2] suggest that this might be due to the increase in carrier lifetime due to trap filling. Another possible explanation is that it is due to a reduction in the effective thickness due to charge neutralization near the electrodes, i.e., a distortion of the electric field in the diamond that leads to an "effective gap" that is much smaller than the real gap. This is analogous to gap reduction in a plasma-filled, bi-polar, Langmuir-Child diode.

The model presented in Eq. (1) shows the functional dependence of the forward current density on the forward voltage drop and the switch thickness. The forward current density increases as the cube of the voltage and decreases as the fifth power of the switch thickness. However, as was illustrated above, Eq. (1) does not accurately determine the magnitude of the forward current density. It was found [2] that Eq. (1) predicted the current density for a 10 μm thick switch that was experimentally measured in a 50 μm thick switch. The authors postulated that this was because trap filling causes an increase in the carrier lifetime. An increase of the carrier lifetime from 1 ns to 3.125 μs is very plausible and would explain the result. Another possible explanation is that the effective switch thickness reduces to 20% of the diamond thickness because of the charge neutralization and field distortion that is produced in the switch volume near the electrodes by the electron beam.

The on-state voltage of a switch depends upon the on-state resistance of the switch and the current conducted by the switch. The on-state resistance depends upon the resistivity of the switch. Electron-induced conductivity in diamond directly affects only the resistivity of the diamond material. The on-state voltage that the switch exhibits depends also on the switch thickness and area chosen for the particular experiment. Thus a more important parameter is the on-state resistivity of the switch. Using Ohm's law, Eq. (1) can be re-written to show the functional dependence of the forward conduction current as a function of the resistivity and thickness of the switch as:

$$J_d = d / \sqrt{(\varepsilon_r \varepsilon_o \mu_n \mu_p \tau \rho^3)}, \qquad (2)$$

When cast in the manner shown in Eq. (2), the switch forward current increases as the switch thickness and decreases as the three-halves power of the resistivity. This is an important point. If the same conductivity can be induced in a thicker diamond slab, the forward current density that the switch can handle will increase linearly. In terms of the physics of diamond switching, a missing piece is the functional dependence of the resistivity with the incident electron beam energy, intensity and diamond thickness.

Figure 3 shows the switch forward current density as a function of diamond thickness for three different on-state resistivities. These curves are calculated from Eq. (2) with the free parameters based on the empirical data presented in Ref [2]. For the diamond switches used in these experiments the switch thicknesses are 65 μm and 100 μm. A forward current density ranging from several hundred A/cm² to several thousand A/cm² is expected depending upon the on-state voltage.

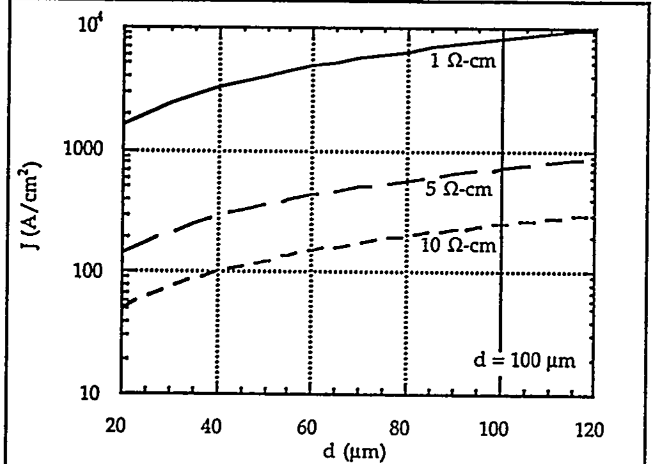

Figure 3: Empirical model showing the forward current density J as a function of switch thickness d for on-state resistivities of 1 Ω-cm, 5 Ω-cm and 10 Ω-cm. The switch thickness used in these experiments is shown by the vertical line.

The on-state resistivity is an extremely important parameter for practical switch design. For example, consider a switch thickness of 20 μm (required for blocking voltages ≈4 kV). If the on-state resistivity of the switch was 1 Ω-cm, the graph in Fig. 3 shows that the conduction current density is ≈1500 A/cm². A diamond switch capable of conducting 3 kA would require an area of ≈2 cm² and have an on-state resistance of ≈1 mΩ. This corresponds to an on-state voltage of ≈3 V at the full conduction current of 3 kA, and a dc blocking voltage of 4 kV.

4. RESULTS AND DISCUSSION

Figure 4 shows switching data at a dc bias voltage of 1000 V. Figure 4(a) shows the conduction current through the diamond switch. The peak current was observed to be ≈18 A. This was primarily limited by the 50 Ω termination in the conduction circuit. Figure 5 shows the peak current delivered by the test-stand when the diamond switch was replaced by a short circuit. As seen in the figure the peak current the circuit is capable of delivering is 19.5 A. The on-state voltage, measured by the capacitively coupled resistive voltage divider shown in Fig. 2, is shown in Fig. 4(b). The on-state resistance of the switch, calculated as the ratio of the on-state voltage and the conduction current is shown in Fig. 4(c). The scale in this figure is expanded to show resistance only to 1 kΩ to show the near zero switch resistance in the conduction phase. Figure 4(d) shows the electron beam diode voltage. For this shot the peak electron beam energy was 150 keV.

The temporal history of the diamond conduction current does not appear to exactly follow the electron beam voltage history. This is due to two factors. First, there is a turn-on delay in the electron beam which accounts for the slight time lag between the electron beam voltage (Figure 4(d)) and the conduction current (Figure 4(a)) traces. Second, the voltage monitor used to measure the diode voltage was not properly compensated, leading to a "droop" which masks the true temporal behavior of the electron beam voltage. In particular, the turn-off time of the electron beam voltage appears to be extended, since the switch stops conducting prior to the diode voltage returning to zero. A Faraday cup would show the electron beam history more accurately and confirm that the conduction within the diamond ceases when the electron beam is turned-off.

Extremely efficient switching was observed. At peak conduction ≈18 A were conducted by the switch (current density ≈550 A/cm²) with an on-state resistance of ≈2-4 Ω. Part of this resistance is due to the contacts and the electrodes deposited on the diamond. No effort was made to optimize the metal electrodes or contacts in these experiments.

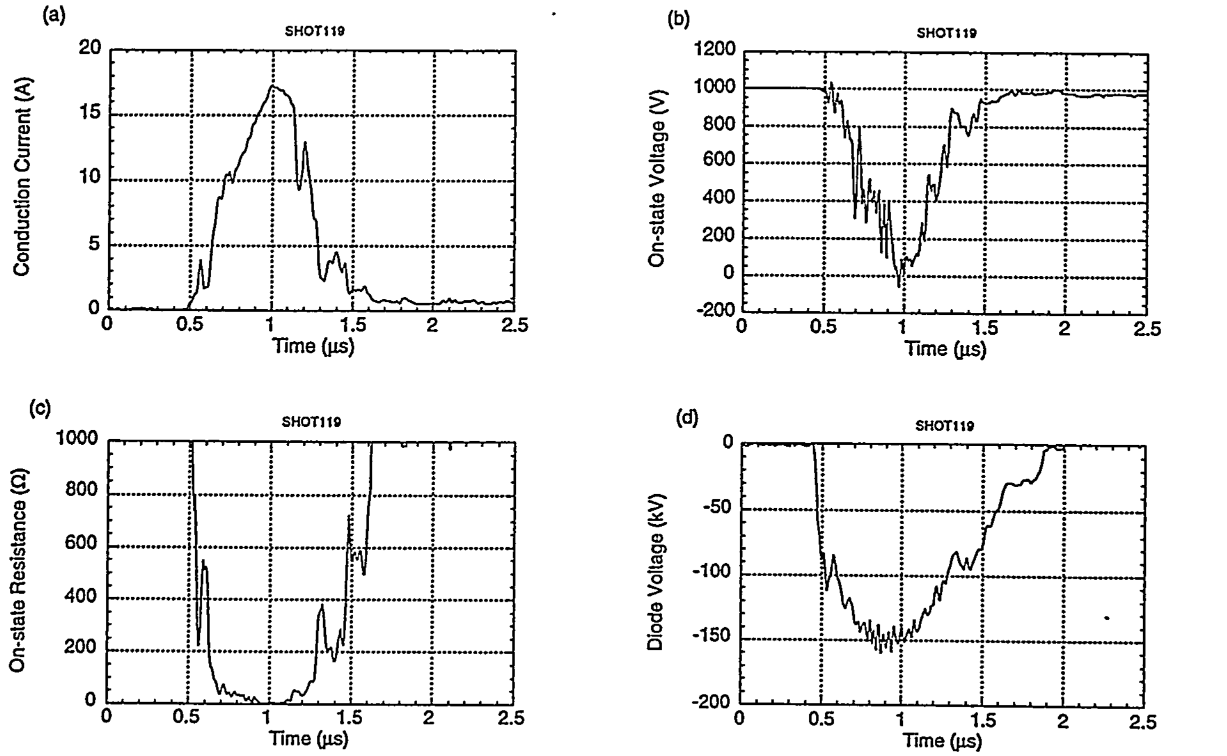

Figure 4: Diamond switching data at 1000 V dc blocking voltage. (a) Forward conduction current. Peak forward conduction of ≈18 A is observed. (b) On-state voltage across the diamond switch. (c) On-state resistance of the switch, calculated as the ratio of the on-state voltage and conduction current. (d) The voltage across the electron beam diode.

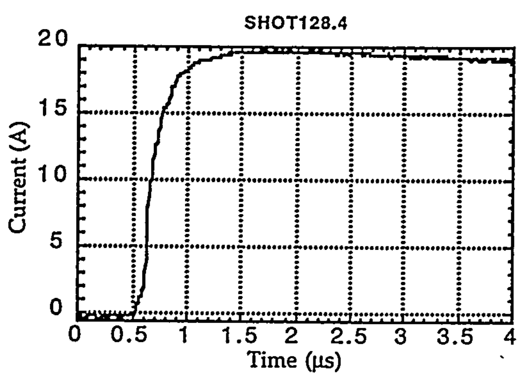

Figure 5: Short circuit current from the test stand circuit shown in Figure 2 at a 1000 V bias. The diamond switch was replaced by a short circuit. The peak current that the circuit can deliver is 19.5 A, limited by the 50 Ω resistor.

The active area of the switch was 0.0314 cm^2 (the 2 mm diameter metal electrodes were the only portion of the diamond irradiated by the electron beam). The diamond thickness was 100 µm. Therefore, the on-state resistance calculated (from the measured conduction current and on-state voltage) in these experiments corresponds to an on-state resistivity of 7.5 Ω-cm. The empirical model presented in the previous section predicts a conduction current density of ≈400 A/cm^2 for a 100 µm thick diamond with 7.5 Ω-cm on-state resistivity. The experimental value is in good agreement with the prediction of the model.

The on-state voltage returned to the bias value after the e-beam was turned off. This is an important feature of diamond useful for repetitive switch operation and opening switch applications, such as solid state circuit breakers and high power microwaves.

The experiments described in this paper used an available electron gun at Sandia National Laboratories, which was not optimized as a trigger for a diamond switch. This gun produces an electron beam whose energy can be varied from 100 keV to 150 keV. A limited scaling of the on-state resistivity with electron beam energy was also conducted at 1000 V dc bias. Figure 6 shows the results of this scaling experiment. The on-state resistivity decreases with an increase in the electron beam energy. To understand the reason for this on-state resistivity decrease it is necessary to study the electron penetration in the diamond sample. Recall that the electrode through which the electrons must penetrate is 600 Å Ti, 1200 Å Pt and 1 μm Au. This thick layer of gold is responsible for electron beam attenuation that necessitates the high electron energies required for efficient switching. Electron transport in the diamond was simulated using a Monte Carlo code. This code and the calculations performed with it are discussed elsewhere.[5]

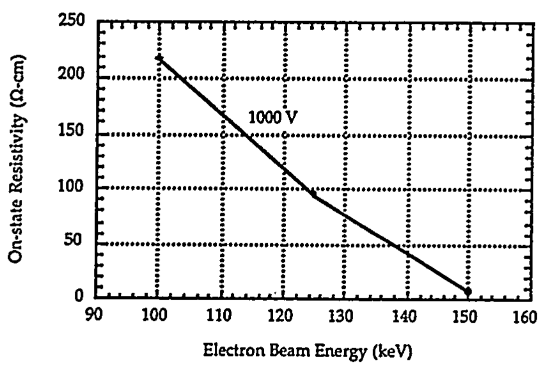

Figure 6: Scaling of the on-state resistivity with the incident electron beam energy. For these experiments a bias voltage of 1000 V was used.

5. DISCUSSION

The experiments conducted during the Phase I program have clearly demonstrated the feasibility of a 1000 V/1000 A switch. Forward conduction current densities in excess of 500 A/cm^2 have been demonstrated at 1000 V dc blocking voltages. These current densities imply that a practical switch operating at 1000 A will require a $\approx$2 cm^2 active area switch. Electronic grade CVD diamond is already available in these sizes. Due the limited budget of this program, work was performed on borrowed diamond samples that were 100 μm thick. The same switches were able to hold off 20 kV dc (2 MV/cm) when tested as part of another on-going program at AASC to develop high voltage switches for the power distribution industry, funded by the Electric Power Research Institute. A practical 1000 V switch will thus be only 10 μm thick (at a maximum).

The on-state resistivities demonstrated in these experiments were around 7 Ω-cm. With almost no optimization, this number may be dropped to 5 Ω-cm and further reduced to 1 Ω-cm with optimization of the metal contacts on the diamond and of the connection of these contacts to the external circuit. An on-state resistivity of 1 Ω-cm implies that the 1000 V/1000 A switch will have an on-state voltage of 0.5 V. Even in the unoptimized case of 7 Ω-cm the diamond switch will have an on-state voltage of only 7.5 V. This switch will be extremely efficient since power losses range from 0.5 - 7.5 kW for a transmission of 1 MW or 0.05% - 0.38%.

The electron beam control for the diamond switch can also be optimized. For better transport of electrons the metal electrodes on a practical switch might be 200 Å Ti, 200 Å Pt and 1000 Å Al. An electron transport simulation for a 44 keV electron beam through a 10 μm thick diamond switch with the metal electrodes described above was conducted. 15.5% of the electrons (3.8% of the electron energy) are transported through the diamond to the opposite electrode. The electron beam energy might be further reduced to allow only 3.6% of the electrons to be transported to the opposite face as in the case of the 150 keV beam used in these experiments. The low on-state resistivities observed in these experiments might then be expected for the 10 μm thick diamond switches. A $\approx$30-40 keV electron beam might be generated using conventional TV/CRT technology that is compact, efficient and has a long lifetime.

Acknowledgements

The authors would like to thank Mr. Damien Conlon of AASC for his support in preparing the diamond samples used in this work. This work was supported by the US Air Force under Phase I STTR contract # F33615-95-C-2565 and by United States Department of Energy under contract DE-AC04-94AL85000.

References

1. K. G. McKay, Phys. Rev. 74, 1606 (1948), and K. G. McKay, Phys. Rev. 77, 816 (1950).
2. R. D. Scarpetti, et. al. "High power electron-beam induced switching in diamond," 9th IEEE Intl. Pulsed Power Conf. Albuquerque, NM (1993).
3. S.-H. Lin, L. Sverdrup, K. Garner, E. Korevaar, C. Cason and C. Phillips, "Electron beam activated diamond switch experiments," SPIE O-E Lase '93, Vol. 1873 (1993).
4. R. P. Joshi, M. K. Kennedy, K. H. Schoenbach and W. W. Hofer, J. Appl. Phys. 72, 4781 (1992).
5. R. R. Prasad, G. Rondeau and G. Loubriel, Phase I STTR Final Report, AASC Tech. Memo # aasc96TM-10, March 8, 1996.