High Voltage, fast turn-on and turn-off switch: Final report

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by

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* Introduction

In early 1998 Alameda Applied Sciences Corporation (AASC) proposed to develop a new type of high voltage, high power diamond switch potentially capable of switching MW power levels at 100's of kV. AASC had previously developed diamond switches with electron beam triggers. These switches handle 10-15 kV voltage pulses with <50 ns rise/fall times and switch 10-100 A at temperatures up to 375 °C with on-state properties comparable to Si and SiC devices. The electron beam triggered switches require 100-300 keV electron sources to trigger switches handling 5-15 kV.

AASC has already enjoyed funding for the electron beam triggered diamond switch. AASC has received a Phase II STTR from the USAF and Phase Is from DTRA and BMDO to develop different aspects of the electron beam triggered diamond switch. AASC has shown that polycrystalline CVD diamond can be used for switching at voltages up to 15 kV, switching 10 A at conduction current densities of 1 kA/cm². We have scaled switch conduction areas from 1 mm² to 12.6 mm² and demonstrated operation at up to 375 °C and 160 A. The on-state specific resistances of these switches are comparable to those of Si and SiC switches. Conduction current rise and fall-times of ≈50 ns were measured, consistent with the trigger electron beam turn-on and turn-off times. These suggest the capability of switching at repetition rates in excess of 10 MHz.

The aspect to be investigated during this contract was an-e-beam triggered diamond switch to be used in high power modulators. Today's high power modulators require higher voltage switches than those developed to date. Specifically, the proposed 1 TeV linear collider, the NLC/ILC at the Stanford Linear Accelerator Center (SLAC), consists of two linacs with 6600 X-Band klystrons powered by 3300 high power modulators.[1] These modulators require switches capable of handling 80 kV, switching 8 kA with pulse durations ranging from 2 μs (linac) to 6 μs (pre-linac) with switching times <50 ns at pulse repetition frequencies up to 180 Hz. In addition the large number of switches and other components dictate a pulse to pulse jitter of <10 ns and a mean time between failures of at least 50,000 hours. The present approach is to use hydrogen filled thyratrons. While these switches meet the voltage and conduction current requirements they lack the required reliability (pulse to pulse jitter) and lifetime. Research to improve these aspects is in progress. A solid state switch inherently offers the required reliability and lifetime. However, Si-based switches developed to date are limited to about 5 kV and several must be stacked in series to deliver the required voltage. This further increases the already large parts count and compromises reliability and lifetime. A monolithic, solid state switch capable of

meeting all the requirements for X-Band modulators would be ideal. DOE selected this proposal for a Phase I SBIR award and this final report describes the progress made during the contract.

Phase 1 assessments

The primary technical objective of the Phase I program was to demonstrate that high voltage switching using an electron beam triggered diamond switch can be achieved with <50 ns rise and fall time and $>2\mu\text{s}$ conduction time. In order to achieve this objective AASC was to perform three tasks in Phase I.

Task 1: Design and fabricate a 50-80kV/ 2 kA/cm² switch package.

Task 2: Demonstrate 50-80kV hold-off. Demonstrate conduction current densities of up to 1kA/cm² with conduction times in excess of $2\mu\text{s}$ and switching times $<50\text{ns}$.

Task 3: Design a prototype switch to be tested in phase II that will validate an efficient reliable high power, high voltage switch

The Phase I program did not fully achieve the goal for Tasks 2. High voltage hold-off could not be shown due to problems with the quality of the CVD diamond. The main supplier of the CVD diamond DeBeers in the Netherlands had changed its CVD growth process in order to achieve more growth in a shorter time. Because of this the diamond quality has worsened leading to a decreased voltage hold-off. Experiments performed during this contract period were therefore performed mostly with natural diamond which due to its limited dimensions could not provide the necessary hold-off. Task 3 was completed by providing a model which, based on the obtained results, delivers a model of the conduction physics in the diamond that can serve as a tool for designing diamond switches for a variety of applications. Results from each task are summarized in the following paragraphs:

Task 1: Design and fabricate switch packages. Several switch packages were built.

Task 2: Demonstrate voltage hold-off, current density and switching times. All CVD diamond packages failed to hold-off more than 5kV. Therefore only low voltage/high current density packages were fabricated. Numerous tests were performed with natural diamonds which due to their inherent size limitation were not able to produce data at more than a few kV. $4\mu\text{s}$ conduction has been shown.

Task 3: Design a prototype switch: Based on the data obtained during the duration of this contract a model has been developed to determine the feasibility of using natural diamond as a

basis for a high voltage, high current switch. The use of natural diamond was proposed because of the higher reliability of the quality of the natural diamond compared to CVD diamond. The inherently small sizes of natural diamonds (≤ 7 mm dia. for disks or $3 \times 2 \times 0.5$ mm for oblongs) have been taken into account. The model has shown that an efficient and reliable diamond switch is nevertheless possible using series stacks of smaller natural diamonds.

The Phase I project has answered all questions of feasibility:

* Is it possible to produce a diamond switch that can hold-off high voltages? The CVD diamonds we tested failed to hold-off >5 kV. This was due to a change of the growth process by DeBeers. However, it has to be said that earlier batches of diamond have proven that CVD diamond is a suitable material. Natural type IIa diamond shows a very reproducible behaviour but can only be acquired in small sizes due to the high price of gemstones. Therefore the hold-off of a single diamond switch device is limited to a few kV.

* Can diamond switches be operated for long conduction times with fast turn on/off times and conduct high current densities? Experiments have shown that the diamond switch depends strongly on the quality of the trigger source. If the e-beam is incident on the diamond for a few microseconds the diamond will conduct for exactly this period. If the risetime of the e-beam radiation can be tuned to be less than a few nanoseconds, the rise-time of the conduction current will follow. High conduction current densities have been achieved with adequate irradiation.

Can an e-beam triggered diamond switch be an efficient and useful device? Based on the acquired data a model has been developed describing the conduction physics in the diamond when irradiated with a strong electron beam. It has been shown that such a device can in fact be operated in an efficient way and provide a highly controllable high voltage switch for special applications. For example, a 25kV/240A switch for rail traction applications might be designed that switches 3MW (at 50% duty factor) and dissipates <180 kW (6%) in the trigger and the switch.

Task 1: Design and fabricate a 50-80kV/ 2 kA/cm² switch package

A switch package which can be used for high voltage testing has been developed. This design is shown in Figure 1. The diamond membrane is sandwiched between two electrodes – the lower a solid cylinder of copper, the upper a cone of copper with an aperture to allow the electron beam to penetrate the diamond. The two electrodes are held together by means of compression springs. The diamond is located within a macor holder. This holder was designed for an earlier (AF-STTR) experiment to show the high temperature operation of the diamond switch.

Figure 1: Typical switch geometry. The control radiation (electrons, for example) is incident upon one of the faces that makes electrical contact with the external circuit.

To make a good electrical contact, the side of the diamond facing away from the e-beam is metallized with 200Å of Ti, 200Å of Pt and 5000Å of Au. That side of the diamond sample is contacted to a copper base, which is connected to the high voltage bias. To minimize electrical resistance and provide more transparency to the e-beam, the side facing the e-beam is metallized with 200Å of Ti, 200Å of Pt and 1000Å of Au. The switch is bi-directional and the polarity of the electrodes may be interchanged with no change in operating characteristics.

Figure 2: Conduction current through a 100-μm CVD diamond mounted using spring loaded contacts. The dc bias voltage was 1000 V. The figure also shows the electron current measured by a Faraday cup in close proximity to the diamond.

A 100- μm thick CVD diamond was placed in this mount without solder or wire bonds and switched. Figure 2 shows the conduction current in the diamond with 1000 V dc bias. It also shows the trigger electron current as measured by a Faraday cup located in close proximity to the diamond. From the conduction current of ≈ 19 A, the on-state resistivity was deduced to be 4 $\Omega\text{-cm}$.

The use of spring loaded contacts instead of solder and wire bonds makes the process of fabricating diamond switches cheaper and quicker. Another level of complexity would be removed if the diamond could be mounted directly without metallization. By doing this a triple point would be removed which should increase the voltage hold-off of the package. This has been tested during an earlier contract where the spring-loaded contacts were also used to measure the on-state resistivity of a bare CVD diamond with no metal coating. While the diamond does conduct when triggered by the electron beam, the on-state resistivity was higher than that measured with metallic contacts. At a dc blocking voltage of 1000 V, the measured on-state resistivity was 139 $\Omega\text{-cm}$, corresponding to a 116- Ω resistance for the 100- μm thick 1.2- mm^2 active area diamond. This factor of ~ 20 higher resistivity without Ohmic contacts could be an issue for practical switches.

Figure 3 shows the geometry, in cross-section, of the diamond switch and spring loaded contacts. It is clear from the figure that in the case of metallized diamonds the current traverses only the thickness of the diamond. In the case that the diamond is not metallized the current must flow parallel to the diamond faces within the diamond to reach the low resistance metal contacts to the external circuit. In this case, the resistance of the diamond is higher.

Figure 3: Geometry of conduction within the diamond switch (a) with no metallization and (b) with metallization. The metallization is depicted in gray.

Simple geometrical estimates suggest that the higher resistance of the unmetallized diamond is as expected. With the assumption that the current density within the diamond is uniform, it is possible to estimate the resistance of both configurations. First, consider the configuration of Figure 3(a):

The current flowing within a disc of radius r in the diamond disc is

$$I(r) = J\pi r^2, \quad (A1)$$

where J is the current density. The differential resistance dR of a disc of radius dr and thickness t is

$$dR(r) = \frac{\rho dr}{2\pi r t}, \quad (A2)$$

where ρ is the resistivity of the diamond. Thus the voltage drop across this differential element is

$$dV(r) = I(r)dR(r) = \frac{J\rho r dr}{2t}, \quad (A3)$$

The voltage integrated over the entire diamond disc is thus

$$V = \int_0^{r_o} V(r) dr = \frac{J\rho r_o^2}{4t}, \quad (A4)$$

where r_o is the radius of the diamond disc. The resistance of the diamond disc is thus

$$R = V/I = \frac{J\rho r_o^2}{4t} / J\pi r_o^2 = \frac{\rho}{4\pi t}. \quad (A5)$$

For the configuration of Figure 3(b), the resistance is:

$$R_2 = V/I = \frac{\rho t}{\pi r_o^2} \quad (A6)$$

Thus:

$$\frac{R}{R_2} = \frac{r_o^2}{4t^2} \approx 10 \quad (A7)$$

for the 0.625-mm diameter, 100- μ m CVD diamond used in the earlier experiments. The measured ratio was ≈ 23 . This is within a factor of 2 of the calculated value (Eq. A7). This discrepancy

might be explained because the current density in the region of the contact must be very high, potentially reaching a limit beyond which current conduction is limited. Such a limit might account for the increased resistivity. Another possibility is that the contact between the metal electrode and the diamond is not very good because whereas the diamond is highly polished, the electrode surface is not, creating a smaller effective area of contact and increasing the resistance of the contact..

Task 2 Demonstrate 50-80kV hold-off. Demonstrate conduction current densities of up to 1kA/cm² with conduction times in excess of 2 μ s and switching times <50ns.

Three electron guns were used during the course of this contract. Two field emitting guns and one thermionic emitting gun. The two field emitting guns can be distinguished by their current density. The gun with the higher current density, higher energy and shorter conduction time will be conveniently called the SNL gun and the gun with the lower current density, lower energy and longer pulse length will be called the Irvine gun.

First, the field emitting e-guns that were used as a trigger are briefly described. Both have a similar working principle therefore only one description is given here. Figure 4 shows a schematic drawing of the experimental arrangement. A 20-30 kV capacitor is discharged by a spark gap into the primary of a 6:1 transformer. The secondary is connected via oil insulation and across an insulator, to the stalk of the e-gun cathode in vacuum. The e-gun diode itself consists of a $\approx$ 12 mm diameter array of carbon fiber bundles placed in a 100 mm ss disc shaped in a Pierce geometry. The anode is a ss mesh placed 4.75-cm in front of the cathode. The un-collimated e-beam that emerges from the mesh travels 10 cm before impinging upon the diamond. With a typical gain of $\approx$ 6:1, the 20-30 kV primary voltage is amplified to 120-180 kV at the cathode stalk. Due to impedance mismatches at the diode end of this circuit, there is a slight "ring-up" of the voltage, making the peak voltages at the cathode as high as 200 kV for a 30 kV charge.

Figure 4: Experimental arrangement used to measure the on-state resistivity of natural and CVD diamonds.

Figure 5 shows representative data from the electron beam system. Figure 4(a) shows the electron beam diode voltage. The peak voltage was ≈ 200 kV with a pulse width (FWHM) of about $0.5 \mu\text{s}$. The peak electron beam current density is $\approx 2 \text{ A/cm}^2$. Figure 4(b) shows the electron beam current density about 100 mm downstream of the cathode (at the location of the diamond sample) as measured using an unbiased Faraday cup. There is also a secondary peak in the current densities shown.

Figure 5: Typical voltage and current density traces for the ≈ 120 -200 keV e-gun.

With this electron gun tests were performed in order to obtain high on-state current density. A simple bias circuit was used in which capacitor was charged to the bias voltage. This capacitor was discharged using an external resistance which was reduced in order to increase the current density. High electron beam energies had to be used to penetrate the diamond. Some of the data are listed in table 1. The first resistance used was 13.8k Ω . The diamond used was a 150 μ m thick/5mm diameter natural diamond with a 3mm spot size on top and bottom which gave an effective a conduction area of 4.9mm².

Table 1: data obtained with SNL gun

primary charge, kV	Bias V	diam_current (A)	leak(mA)	diamond Ω	ebeam energy (eV)
25	0	<0.1	0		226240
25	5000	0.18	0		226240
25	5000	0.16	0		230720
25	5000	0.19	0		230720
reduced resistance to 7.1k Ω					
25	5000	0.7	0	42.8571429	217280
25	5000	0.7	0	42.8571429	212800
25	5000	0.668	0	385.02994	239680
reduced resistance to 1k Ω					
25	5000	6.78	0	-262.53687	230720
25	5000	7	0	-285.71429	221760
reduced resistance to 110 Ω					
25	5000	42	0	9.04761905	230720
25	5000	42	0	9.04761905	235200
25	5000	44	0	3.63636364	230720
reduced resistance to 10 Ω					
25	5000	210	0	13.8095238	230720
reduced resistance to 0 Ω					
25	5000	316	0	15.8227848	257600

As can be seen from the data a current of 316 A was conducted through the diamond.

This produces a current density of 6.3kA/cm², which is well above the required 1kA/cm² for this task.

AASC has also used a thermionic source of electrons to enable experiments with longer conduction times. The thermionic source was assembled within a stainless steel vacuum chamber. The system has been pumped down to a low base pressure of $\approx 9 \times 10^{-9}$ Torr. Figure 6 shows the overall arrangement of the electrodes within the vacuum housing. The cathode assembly is designed with no sharp corners to permit operation at voltages up to 200 kV. The design also provides electrostatic focusing using A Pierce gun type geometry.

ALAMEDA APPLIED SCIENCES CORP. 2235 POLVOROSA AVE. SUITE 230 SAN LEANDRO, CA 94577 Tel: (510) 483-4156 Fax: (510) 483-8107				Title Thermionic Cathode Assembly	
Drawn by John Edighoffer		Date 3/5/98		Materials Scale 1:2 Drawing Number AASC98D0007	
Checked by _____		Date _____		Tolerances (unless otherwise specified) X.X ±0.1 X.XX ±0.02 X.XXX ±0.002 Dimensions in inches	

Figure 6: Schematic diagram of the cathode and anode within the vacuum chamber.

. With the thermionic source, the voltage stays flat-topped for about 2 μ s. The current in the beam can also be varied independently of the beam voltage. The current can be changed by changing the temperature at which the thermionic cathode is operated, while the voltage is changed by the charge voltage on the pulse-forming network.

The total cathode current is measured in two ways and the electron beam profile is measured as a function of distance from the cathode. The exit of the anode hole is covered with an insulated metal mesh. This mesh intercepts 36.3% of the beam.

The following trace (Figure 7) shows the beam current as measured with the insulated anode mesh. The monitors were terminated into 50 Ω , so the current is 1/50 the voltage measured.. The anode mesh monitor measured 5.9 V which gives a beam current of 118 mA intercepted by the mesh. Since the mesh transparency is 63.7%, this implies a total beam current of 325 mA. :

Figure 7: Beam current measurement using the insulated anode mesh monitor.

With this source we were able to show a 4 μs conduction time at a bias voltage of 400V and a conduction current of 7A. The current rise and fall times were less than a 100ns which is very close to the requirements of this phase I.

Figure 8: $\approx 4 \mu\text{s}$ conduction current through the diamond

So most of the goals of task 2 have been accomplished. It has been shown that the diamond can conduct a current density of $>6\text{kA/cm}^2$ and it can be switched for more than $4\mu\text{s}$ with rise/fall times of less than 100ns.

Task 3: Design a prototype switch to be tested in phase II that will validate an efficient, reliable, high power, high voltage switch

Due to the fact that the CVD diamonds failed beyond $\approx 5\text{ kV}$, a study was done in order to make sure that an effective switch package can be made with natural diamonds. This part presents an analysis of recent data obtained from natural Type IIa diamonds that were triggered by both the SNL and the Irvine e-guns. All the data reported here were obtained from a *single* Type IIa diamond that is $3 \times 1 \times 0.5\text{ mm}$ with the $1 \times 0.5\text{ mm}$ faces metallized. The electron flux from the SNL gun had a typical value at 200 keV beam energy of about 12 A/cm^2 , whereas that from the Irvine gun at the same energy was about 0.6 A/cm^2 , a factor of $\times 20$ lower. The SNL gun was operated at peak e-beam energies ranging from 90-250 keV, whereas the Irvine gun data span a more limited range from 120-200 keV. The data from the two guns were obtained using a single diamond assembly along with a single bias circuit. Analysis of the data obtained from the two guns reveals a power law correlation of on-state resistance with e-beam flux and energy, as

$$R[\Omega] = \frac{3 \times 10^5}{(\phi \cdot \epsilon)^{1.3}}. \text{ A simple physical model is proposed that explains this correlation. To drive a}$$

diamond into high conductivity requires triggering with high beam energies. For a field emitter, the electron flux is directly linked to the beam energy (diode voltage) by the Child-Langmuir law, so beam energy is the only controlling parameter. Since ϕ itself scales as $\epsilon^{1.5}$ for a Child-Langmuir diode, the resistance scales as $\epsilon^{3.25}$. The exponent of 3.25 is not very precise. The scatter in these data sets is sufficiently large that exponents in the range of 3.25-3.75 would all provide reasonable fits. What is significant is that the on-state conductivity increases so strongly with beam energy. This strong scaling with e-beam energy has important implications for design of such switches.

Experimental data

Figure 9 shows the data from the SNL gun. These data show a decreasing trend from $100\ \Omega$ to about $1\ \Omega$ as the beam energy is increased from 100-300 keV. One data point that shows a $0.3\ \Omega$ resistance at 230 keV is ignored for the moment.

Column three of Table II shows the measured e-beam flux using a Faraday Cup located near the diamond. Column four shows the calculated e-beam flux using the Child-Langmuir law:

$$\phi = 2 \times 10^{-6} \left[\frac{\epsilon^{1.5}}{d^2} \right] \left[\frac{1}{R^2} \right], \frac{A}{cm^2} \quad (1)$$

where ϵ is the beam energy in eV, d the diode A-K gap in cm. and R^2 represents the factor by which the flux has decayed at the location of the Faraday Cup due to space charge blow up of the beam. While the measured data show large fluctuations, the mean value of the column is 12 A/cm². The mean value of column four is 11.66 A/cm², which suggests that the flux is well represented by the Child-Langmuir law at the diode followed by some space charge expansion of the beam. The data of column four are for numerical values of $d=2$ cm and $R=1.94$ i.e. it is as if the ≈ 1 cm beam at the source has expanded to an ≈ 2 cm dia. beam at the Faraday Cup. This is reasonable and in any case a measurable parameter. With these parameters, Eq. 1 becomes:

$$\phi = 2 \times 10^{-6} \left[\frac{\epsilon^{1.5}}{15} \right], \frac{A}{cm^2} \quad (2)$$

Figure 9: Measured on-state resistance vs. beam energy ϵ (keV)

Using the theoretically calculated flux ϕ (column four of Table 2), three different power law expressions for the resistance vs. ϵ were considered. They are:

$$R \propto \left[\frac{1}{(\phi \epsilon)} \right], \quad R \propto \left[\frac{1}{(\phi \epsilon)^{1.3}} \right] \text{ and } R \propto \left[\frac{1}{(\phi \epsilon)^2} \right] \quad (3)$$

These power laws were chosen in order to see whether they pointed to a strong correlation with a particular dependence of resistance on beam energy and flux. Such a correlation would then motivate development of a phenomenological model for on-state conduction

Table 2. Data from SNL gun

Measured Resistance, Ω	e-beam energy, keV	Measured e-beam flux, A/cm^2	Calculated Child-Langmuir flux ϕ , A/cm^2
32.943	116.53	8.0000	5.3042
111.39	117.70	11.300	5.3837
105.50	127.92	7.4000	6.1005
51.850	135.58	6.8000	6.6560
58.938	138.51	8.7000	6.8733
3.8444	158.62	10.600	8.4236
26.611	177.79	9.8000	9.9958
51.643	186.63	12.400	10.750
12.018	196.67	17.400	11.629
22.640	199.82	11.000	11.909
4.0638	201.17	15.100	12.031
34.954	201.38	8.9000	12.050
12.028	208.86	13.200	12.727
6.2989	225.22	12.800	14.251
6.7846	226.53	12.400	14.376
6.6574	229.91	12.100	14.699
8.4773	230.19	11.800	14.725
0.30786	232.68	17.800	14.965
5.4877	236.72	12.900	15.357
7.4466	239.15	12.200	15.594
4.9701	244.09	17.800	16.079
7.6484	248.83	13.500	16.550
Mean value		11.99 A/cm^2	11.66 A/cm^2

. Figure 10 shows the data of Fig. 9 with the power law fits that used the values of ϕ from Eq. 1 and the measured values of ϵ .

Figure 10: Data from SNL gun compared with three assumed Power Laws.

It would appear that the power law $R \propto \left[\frac{1}{(\phi \epsilon)^{1.3}} \right]$ is the best fit to the data. Based on the

fit, this power law becomes:

$$R_{SNL}[\Omega] = \frac{3 \times 10^5}{\left\{ \phi_{SNL} \left[\frac{A}{cm^2} \right] * \epsilon [keV] \right\}^{1.3}} \quad (4)$$

Figure 3 shows the same data, but with yet another power law, $R \propto \left[\frac{1}{(\phi \epsilon)^{1.5}} \right]$, to demonstrate that the scaling of Eq. 4 is not highly accurate. The scaling of on-state conductivity with ϵ may approximately be stated to lie in the range of $\epsilon^{3.25} (\phi * \epsilon)^{1.3}$ up to $\epsilon^{3.75} (\phi * \epsilon)^{1.5}$.

Figure 11: Data from SNL gun compared with two assumed Power Laws.

How well does this ansatz fit the data obtained with the Irvine gun? Figure 12 shows the data from the Irvine gun with identical power law fits. However, the data for the Irvine gun were fit to a flux given by:

$$\phi = 2 \times 10^{-6} \left[\frac{\epsilon^{1.5}}{300} \right], \frac{A}{\text{cm}^2} \quad (5)$$

This factor of ≈ 20 reduction in beam flux in the Irvine gun (see Eq. 2) is because the emitting area was smaller (≈ 5 mm vs. 10 mm), the A-K gap larger (3.3 vs. 2 cm) and the distance to the diamond was longer. All three factors conspired to reduce the flux from the Irvine gun. The flux may be easily increased by making the A-K gap smaller, the cathode emitting area larger (this reduces beam blow-up) and moving the diamond closer. However, the order of magnitude difference in flux from the two guns has proven to be very useful in enabling us to elucidate a simple model for diamond conduction, as described in the next section.

Figure 12: Data from the Irvine gun compared with three assumed Power Laws.

Fig. 12 shows that the same power law that was the best fit to the SNL gun data also fits the Irvine gun data. What is remarkable is that the numerical coefficient is the same, viz.:

$$R_{Irvine}[\Omega] = \frac{3 \times 10^5}{\left\{ \phi_{Irvine} \left[\frac{A}{cm^2} \right] * \epsilon [keV] \right\}^{1.3}} \quad (6)$$

Not shown in this case is the scaling, $R \propto \left[\frac{1}{(\phi \epsilon)^{1.5}} \right]$, because here it is visibly worse than the scaling given by Eq. 6.

Figure 13: Data from the Irvine and SNL guns compared with the same best fit power law.

Figure 13 shows the data from both guns with the best power law fits. A glance at the data for 200 keV shows that the ratio of on-state resistances for the two guns is $\approx (600/12) = 50$. The ratio of beam fluxes is $300/15 = 20$. Now $(20)^{1.3} = 49$. For the same beam energy, this implies

that the difference in on-state resistance from the two guns is due only to the difference in flux. The remarkable similarity in numerical coefficients of on-state resistance for the two guns (3×10^5) points towards a simple phenomenological model for conduction, which is described next.

Physical Model for on-state conductivity of diamond

Begin with Ohm's law:

$$J = \sigma \cdot \bar{E} \quad (7)$$

$$\frac{I}{A} = \sigma \frac{V}{d}, \text{ thus } V = I \left(\frac{d}{A\sigma} \right) \quad (8)$$

$$R = \frac{d}{A\sigma} = \frac{0.3}{0.1 \cdot \delta \cdot \sigma} = \frac{3}{\delta\sigma} \quad (9)$$

where δ is the depth of penetration of the beam (in cm) into the 0.5 mm thick diamond and σ is the on-state conductivity in mhos/cm.

An earlier Memo. (aasc98TM-28) had introduced a simple power law for penetration of the e-beam into natural diamond. The range formula is from the Radiological Health Handbook, 1970 edition, published by the (now defunct) Department of Health, Education and Welfare.

$$\xi = 412 * E^{\{1.265 - 0.0954 \ln(E)\}} \frac{mg}{cm^2}, \text{ where } E \text{ is the maximum energy in MeV} \quad (10)$$

For a diamond density of 3.5 g/cm^3 , the penetration depth is given by:

$$\delta = 1.18 \times 10^3 * E^{\{1.265 - 0.0954 \ln(E)\}} \mu m \quad (11)$$

Figure 6 plots Eq. 11 and an approximation to Eq. 11, given by Eq. 12.

$$\delta = 1.42 \times 10^{-1} \cdot \epsilon^{\{1.25\}} [\mu m] \quad (12)$$

where ϵ is in keV. Over the range of interest (100-250 keV), Eq. 12 is a good approximation to Eq. 11. The difference between the two curves is between 16 and 20% over this range. (The reason for this approximation will become clear in a moment). Plugging Eq. 12 into Eq. 9 gives:

$$R \approx \frac{2.1 \times 10^5}{\epsilon^{1.25} \sigma}, \Omega, \text{ where } \epsilon \text{ is in keV} \quad (13)$$

The conductivity may be expressed as:

$$\sigma = n \cdot e \cdot \mu$$

(14)

where μ is the mobility of the electrons in the diamond.

Fig. 14: Penetration depth vs. ϵ (keV): comparison of Eqs. 11 and 12 (see text).

The value of μ found in the literature is $\sim 1200 \text{ cm}^2/\text{V}\cdot\text{s}$. The data for the SNL gun show that at $\approx 10 \text{ A/cm}^2$ and 200 keV, the resistance is $\approx 8 \Omega$. The depth of penetration (see Fig. 5 or Eq. 11) is about 150 μm . Thus the measured on-state conductivity is:

$$\sigma = \frac{I}{A \cdot R} = \frac{0.3 \text{ cm}}{0.1 \text{ cm} \cdot 0.015 \text{ cm} \cdot 8 \Omega} \approx 25 \frac{\text{mhos}}{\text{cm}} \quad (15)$$

Eq. 14 then gives: $n \approx 1.3 \times 10^{17} \text{ cm}^{-3}$.

Suppose we assume that the number density of mobile electrons produced in the diamond is linearly proportional to the incident flux (more electrons in, more hole-pairs produced) and linearly proportional to the incident electron energy (i.e. there is a fixed cost of ~15 eV/hole-pair). Then:

$$n \left[cm^{-3} \right] = \frac{\phi \left[\frac{A}{cm^2} \right]}{ev_e \left[\frac{cm}{s} \right]} \cdot \left\{ \frac{\epsilon \left[keV \right]}{15 \times 10^{-3} \left[\frac{keV}{hole-pair} \right]} \right\} \cdot \beta \quad (16)$$

where v_e is the velocity of the incident electrons and β is a scale factor that accounts for the increase in density inside the diamond due to the slowing down of the electrons. The magnitude of this scale factor is estimated as follows:

For 200 keV and 10 A/cm², Eq. 16 gives: $n = 4.1 \times 10^{13} \text{ cm}^{-3} \cdot \beta$. Since Eq. 14 gave $n \approx 1.6 \times 10^{17} \text{ cm}^{-3}$, $\beta \approx 3.18 \times 10^3$ ($1.3 \times 10^{17} / 4.1 \times 10^{13}$). Eq. 16 becomes:

$$n \left[cm^{-3} \right] = 7.37 \times 10^{14} \left(\phi \left[\frac{A}{cm^2} \right] \epsilon \left[keV \right]^{0.5} \right) \quad (17)$$

Eqs. 14 and 17 give:

$$\sigma \left[\frac{mhos}{cm} \right] = 0.142 \left(\phi \left[\frac{A}{cm^2} \right] \epsilon \left[keV \right]^{0.5} \right) \quad (18)$$

Eqs. 13 and 18 give:

$$R \left[\Omega \right] \approx \frac{1.48 \times 10^6}{\phi \left[\frac{A}{cm^2} \right] \epsilon \left[keV \right]^{1.75}} \quad (19)$$

Eq. 19 may be rewritten as :

$$R \left[\Omega \right] \approx \frac{9.4 \times 10^5}{(\phi \epsilon)^{1.3}} \left\{ \frac{(\phi)^{0.3}}{(\epsilon)^{0.45}} \right\} \text{ or } R \left[\Omega \right] \approx \frac{1.48 \times 10^6}{(\phi \epsilon)^{1.3}} \left\{ \frac{\left(\frac{(2 \times 10^{-6} \cdot 10^{4.5} \cdot \epsilon^{1.5})^{0.3}}{15} \right)}{(\epsilon)^{0.45}} \right\} \quad (20)$$

which becomes:

$$R[\Omega] \approx \frac{2.88 \times 10^5}{(\phi \epsilon)^{1.3}} \quad (21)$$

It would appear that the phenomenological power law compares well with the experimentally derived scaling law (see Fig. 13). Needless to say, the agreement to within 4% of the numerical coefficient is inconsequential, given the many approximations that have led us to Eq. 21. Further, even the form of the power law is only an approximation, since Eq. 12 is an approximation to Eq. 11, which is itself an approximation. Nevertheless, it is satisfying to go through the analysis and find such close agreement between a phenomenological model and experiment.

It might be argued that both the experimental data fits and the derivation above could just as well have used a power law with ϵ as the sole parameter, since ϕ is after all, expressed as a function of ϵ for the field emitting guns. We have chosen the particular combination $(\phi * \epsilon)$ because both ϕ and ϵ are independently measurable parameters in the experiment. Also, when the flux is independent of the beam energy, it is more useful. One test that suggests itself is to keep the beam energy fixed but move the diamond farther away from the diode, to measure the resistance versus (decreasing) flux, while keeping the beam energy constant.

The phenomenological scaling law, Eq. 21, compares favorably in form and magnitude with the experimentally measured scaling laws shown in Fig. 5. Further, as discussed earlier, the difference between the on-state resistances in the SNL and Irvine guns is due mainly to the differences in e-beam flux, ϕ , in the two guns. It would appear that this simple model captures the conduction physics of the diamond, without resort to detailed examination of the complex condensed matter physics that actually takes place.

One troublesome feature of this analysis is the form assumed for Eq. 16. There we began with the free electron density in the e-beam, $n_{beam} = \frac{\phi}{e v_{beam}}$, and multiplied it by the "quantum gain" (i.e. the number of hole-pairs produced by each absorbed quantum) and also a scale factor β to account for the fact that when the electrons stop in the diamond, their occupied volume decreases and hence the density increases. An alternate method of estimating the density is to start with the number of electrons absorbed/unit time, divide by the absorption volume and

multiply by the lifetime of the electron and the quantum gain, to derive the density. This expression is:

$$n \left[\text{cm}^{-3} \right] = \frac{\phi \left[\frac{\text{A}}{\text{cm}^2} \right]}{e} \cdot \left(\frac{3 \times 10^{-2} \left[\text{cm}^2 \right]}{0.1 \times 1.42 \times 10^{-5} \cdot \epsilon^{1.25}} \right) \cdot \left(\frac{\epsilon \left[\text{keV} \right]}{15 \times 10^{-3}} \right) \cdot \tau \quad (22)$$

$$= 8.8 \times 10^{24} \phi \epsilon^{-0.25} \tau$$

Eq. 22 gives a density of $1.3 \times 10^{17} \text{ cm}^{-3}$ (see Eqs. 14 & 15) when $\tau \approx 6 \text{ ns}$. This is rather long but perhaps not unreasonable for Type IIa diamond. Also, τ might itself be a function of ϵ . Ignoring this for a moment, Eqs. 22, 13 & 14 are combined to give:

$$R[\Omega] = \frac{1.24 \times 10^{-4}}{\left(\phi \left[\frac{\text{A}}{\text{cm}^2} \right] \epsilon \left[\text{keV} \right] \right) \tau \left[\text{s} \right]} \quad (23)$$

Eq. 23 is checked by plugging in 10 A/cm^2 , 200 keV and 6 ns to get $R \approx 10 \Omega$. Eq. 23 shows a scaling law with $(\phi \cdot \epsilon)$ that disagrees with the fits to the data. But τ might itself depend on ϵ . In fact, Eq. 23 would have the same functional form as Eq. 21 if the lifetime of the electrons in the diamond were to scale as:

$$\tau \propto (\phi \epsilon)^{0.3}, \text{ or } (\epsilon)^{0.75} \quad (24)$$

Such a scaling might be plausible. The deeper the penetration depth, the longer the lifetime, since the same number of pairs are produced further apart.

As one further check on the validity of the model presented here, let us estimate the on-state current density using the calculated mobility, μ . The electron drift velocity is:

$$v_d \leq \mu \cdot \bar{E}, \quad \text{or } v_d \leq \mu \cdot \frac{V_{\text{bias}}}{l}, \quad \text{where } l = 0.3 \text{ cm} \quad (25)$$

For a typical 400 V bias,

$$v_d \leq 1.6 \times 10^6 \text{ cm/s} \quad (26)$$

The predicted current density (at 200 keV and 10 A/cm^2 flux) is therefore:

$$\bar{J} = nev_d \leq 1.3 \times 10^{17} \cdot 1.6 \times 10^{-19} \cdot 1.6 \times 10^6 \leq 33 \text{ kA/cm}^2 \quad (27)$$

The measured current density is,

$$\bar{J}_{meas.} \approx \left[\frac{20 \text{ A}}{0.1 \cdot 0.012 \text{ cm}^2} \right] \approx 17 \text{ kA/cm}^2 \quad (28)$$

If the actual electron drift velocity is a factor of two lower than the maximum given by Eq. 27 (due to scattering off holes, traps and space charge effects), then the current density predicted by the model would also agree with the measurements.

A few other observations from the model are:

- Eq. 23 shows that the transit time across the 3 mm gap is ≥ 188 ns. Since the lifetime of the typical hole-pair produced in the diamond is estimated to be ~ 6 ns, this is proof that electrons must be injected from the cathode to replace those lost to recombination before reaching the anode. It is only if replacement electrons are injected from the cathode that the current density can be as high as observed. In retrospect, Scarpetti et al had suggested this from their measurements, but since no analysis such as this have been performed to date by us, we naively chanted the (incorrect) mantra that no additional electrons are injected from the external circuit. Further, consider our data from CVD diamonds. If the typical lifetime in CVD is 10-100 ps, how could we have observed current densities as high as 8 kA/cm², with e-beam fluxes of ≈ 10 A/cm², unless there was continuous injection of new electrons from the cathode?
- A 500 keV e-beam will penetrate the entire 500 μ m thickness of the diamond. At 47 A/cm² (consistent with 500 keV) the resistance (Eq. 21) will drop to $\approx 0.6 \Omega$. From Eq. 15, σ will be 100 mhos/m and the free carrier density will increase to $5.2 \times 10^{17} \text{ cm}^{-3}$. From Eq. 24, the current density will be $\leq 133 \text{ kA/cm}^2$. The current will therefore be ≤ 667 A. This provides an upper bound to the current that can be carried by a single 3x1x0.5 mm diamond. Of course at such high densities saturation effects will come into play. It is reasonable to suppose that the maximum current density in natural diamond is restricted to about 50 kA/cm², without avalanche breakdown. For the full 1x0.5 mm area, the maximum current would therefore be 250 A. A 25 kV/250 A switch in such a small package would certainly be a major milestone. It should be noted that our recent experiments have come within a factor of three of this current density limit.
- The physics should change significantly as the bias voltage is increased. If the drift velocity continues to increase linearly with bias, then Eq. 25 gives a velocity of $\approx 1 \times 10^8$ cm/s for a 25 kV

bias across a 3 mm gap. The transit time becomes ≈ 1 ns! If the lifetime of the average electron is still ≈ 6 ns, then we might be able to mask the ends of the diamond significantly and still achieve good conductivity.

The simple model presented here provides a practical tool for design of diamond switches. The geometry used in these tests offers a much lower current gain than the previous geometry, in which the e-beam flux is in the same direction as the conduction across a thin diamond membrane. Consider the incident flux of 10 A/cm^2 and the on-state current density of 17 kA/cm^2 . The total e-beam current flowing into the diamond is $10 \times 0.3 \times 0.1 = 0.3 \text{ A}$. The conducted current is 20 A , giving a current gain of just 67:1. Hence a 1 kA switch would require a 15 A trigger current. However, suppose that the 1 kA switch were comprised of 50 parallel switches carrying 20 A each. Suppose also that the net resistance required is 10Ω . Each switch may operate at 500Ω . For a 200 keV beam, Eq. 4 gives: $\phi \approx 0.7 \text{ A/cm}^2$. (Not surprisingly, this estimate agrees very well with the data from the Irvine gun at 200 keV and $\approx 500 \Omega$). The trigger current per switch is then $\approx 20 \text{ mA}$ and the total current required for 50 switches is just 1 A . Note that at 500Ω , the current gain is 1000:1.

The experiments described in this Memo. have increased confidence in our ability to meet the milestones of the DOE project. Now it remains to tackle the challenge of packaging a natural diamond so that it holds off 25 kV and switches $20\text{-}25 \text{ A}$ with $\sim 100 \Omega$ on-state resistance. Then by using serial and parallel switching of the diamond membrane a compact switch could be manufactured for a variety of applications. A tentative design of such a switch is given in Fig. 15.

Fig 15: switch design

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