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# Optoelectronic switching in diamond and optical surface breakdown

E.I. Lipatov, V.F. Tarasenko

*Abstract*. **The optoelectronic switching in two natural diamond samples of type 2-A is studied at voltages up to 1000 V and the energy density of control 60-ns, 308-nm laser pulses up to 0.6 J cm$^{-2}$. It is shown that the design of a diamond switch affects the switching efficiency. When the energy density exceeds 0.2 J cm$^{-2}$ and the interelectrode surface is completely illuminated, the surface breakdown is initiated by UV radiation, which shunts the current flow through the diamond crystal. When the illumination of the interelectrode surface is excluded, the surface breakdown does not occur. The threshold radiation densities sufficient for initiating the surface breakdown are determined for electric field strengths up to 10 kV cm$^{-1}$.**

***Keywords***: *diamond, switch, laser, optical breakdown, switching efficiency.*

## 1. Introduction

A number of applications of high-current electronics require the use of high-power compact solid-state switches operating at high pulse repetition rates. It is assumed that such switches can be based on wide-gap semiconductors because it is necessary to provide a high electric strength and a large specific resistance to avoid the breakdown and minimise the leakage current.

Among a variety of semiconductors that could be used in high-voltage switches, diamond has the most suitable parameters: a high dark specific resistance (more than $10^{12}$ $\Omega$ cm), a large electric strength (above 2 MV cm$^{-1}$), and the highest room-temperature heat conduction (up to 25 W cm$^{-1}$ K$^{-1}$, which is 3 – 5 times higher than that of copper). In addition, diamond is stable and chemically inert with respect to many reagents up to temperatures $\sim 700\,^{\circ}$C, and has a high radiation resistance.

Because the efficient p – n transitions in diamond have not been produced so far, diamond switches should be controlled by externally generated nonequilibrium charge carriers. An electron beam provides the high switching efficiency [1, 2], but it requires the use of a vacuum system and a high-voltage switching control circuit. Because of this, diamond switches are controlled by UV radiation [3 – 12].

To obtain high pulsed current densities, it is necessary to use high-intensity UV radiation. This can induce the surface breakdown of a diamond crystal, which imposes the restriction on the intensity, or more accurately, on the radiation energy density.

The aim of this paper is to study the dependence of the switching efficiency on the electric field strength for switches of different geometries based on the type 2-A diamond controlled by the 308-nm laser radiation. We found that high-intensity UV radiation could initiate the surface breakdown, which shunted the current flow through the crystal, resulting in a change in the dependence of the switching efficiency on the field strength.

## 2. Switching efficiency of a switch

An important operation parameter of a switch is the switching efficiency, which is determined by the switch resistance in the open phase. The switching efficiency of a photoconductor switch controlled by a light pulse is

$$\eta = \frac{U_{\mathrm{m}}}{U_0} = \frac{R_{\mathrm{L}}}{R_{\min} + R_{\mathrm{L}}}, \tag{1}$$

where $U_{\mathrm{m}}$ is the voltage amplitude measured on a load; $U_0$ is the switching voltage; $R_{\mathrm{L}}$ is the load resistance; and $R_{\min}$ is the minimum resistance of the switch.

According to [13], the photoconductor resistance by neglecting the influence of contacts is

$$R = \frac{l}{en\mu S}, \tag{2}$$

where $l$ and $S$ are the length and cross-section area of the photoconductor; $e$ is the elementary charge; and $n$ and $\mu$ are the concentration and mobility of carriers, respectively.

It is obvious that the increase in the radiation intensity leads to the growth of the concentration of nonequilibrium charge carriers in the photoconductor, resulting in the decrease in the resistance and, therefore, in the increase in the switching efficiency. At the same time, the increase in the voltage being switched at the constant radiation intensity reduces the mobility of charge carriers, which is valid for all semiconductors [14] and, in particular, for diamond [15, 16]. This should result in an increase in the switch resistance and a decrease in the switching efficiency with increasing voltage.

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**E.I. Lipatov, V.F. Tarasenko** Institute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences, prosp. Akademicheskii 2/2, 634055 Tomsk, Russia; e-mail: lipatov@loi.hcei.tsc.ru

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Figure 1 presents the dependences of the switching efficiency on the electric field strength, calculated from the data reported in papers [4–7, 13]. Only the behaviour of curve (*4*) corresponded to the dependence consistent with expressions (1) and (2). In other cases, the region of a weak decrease in the switching efficiency at small field strengths changed to the switching efficiency growth region. In this case, the 'anomalous component' appeared in the current pulse of the diamond switch, which distorted the pulse shape [6, 10], caused a considerable increase in the pulse duration [5, 6, 10] or was observed with a delay [5, 7, 12, 13, 15]. The appearance of the anomalous component of the pulsed current was explained by the injection of holes due to accumulation of a volume charge in traps in the near-contact region [4–7, 11], by the optoelectronic instability [13, 15], and the surface breakdown induced by UV radiation [7]. A careful study of the appearance of the anomalous photocurrent component in diamond switches showed that at least in [11] this breakdown was caused by high radiation energy densities. The preliminary results of these studies were presented in [12].

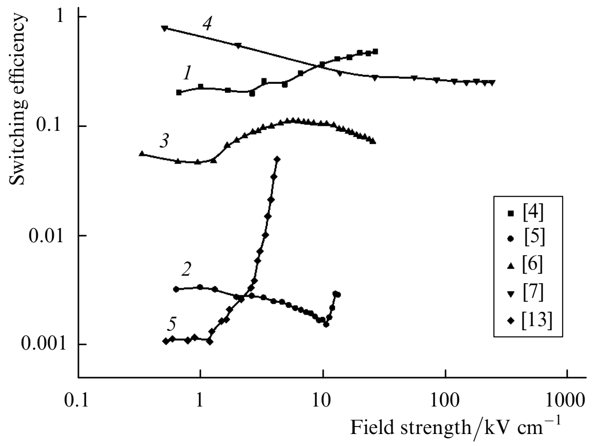

**Figure 1.** Dependences of the switching efficiency on the applied electric field strength, calculated by using data presented in the literature.

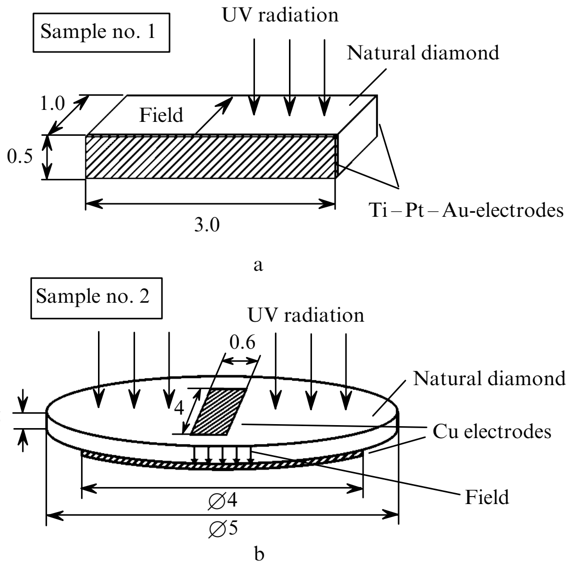

**Figure 2.** Schematic pictures of diamond switches (dimensions are in mm).

## 3. Experimental

We studied optoelectronic switching in two samples shown schematically in Fig. 2. Sample no. 1 was a photodetector (Alameda Applied Science Corp.) based on a natural type-2 diamond single crystal of size $3 \times 1 \times 0.5$ mm placed into a 50-$\Omega$ coaxial holder, as in [9]. Electric contacts to the diamond crystal were fabricated by the successive deposition of Ti–Pt–Au layers on the opposite faces of size $3 \times 0.5$ mm.

Sample no. 2 based on a diamond crystal of the same type was a 0.25-mm-thick disc of diameter 5 mm and had copper contacts produced by vacuum-arc deposition [17]. A circular electrode of diameter 4 mm was deposited on one side of the diamond disc, and a rectangular electrode of size $4 \times 0.6$ mm was deposited on the other side.

The $3 \times 1$-mm face (i.e. the entire interelectrode gap) of sample no. 1 was uniformly illuminated. The radiation propagated orthogonal to the applied electric field strength vector. In the case of sample no. 2, the side with a smaller electrode was illuminated, and radiation propagated parallel to the applied field strength vector. To avoid a breakdown on the surface of sample no. 2, an aperture of diameter 2–4 mm was placed in front of the illuminated side face of the crystal, which is not shown in the scheme.

One of the contacts of the crystal was connected to a load with $R_{\mathrm{L}} = 25$ $\Omega$ and the other – to a capacitor with $C = 67$ nF, which was charged via a restricting resistance from a dc voltage source. The charging voltage $U_0$ of the capacitor was varied from 10 to 1000 V.

Diamond switches were controlled by 308-nm, 60-ns pulses from a LIDA-T laser manufactured at the IHE SB RAS [18].

The resistance of the diamond crystal exposed to laser radiation decreased and the switched capacitor discharged via the diamond resistance and the load. The load voltage was recorded with Tektronix TDS-220 and TDS-224 digital oscilloscopes. The radiation energy was measured with a PE50-BB pyroelectric power meter (Ophir Optronic Ltd.) The methods of measuring the radiation intensity and photocurrent amplitude are described in detail in [10].

## 4. Experimental results and discussion

The type of the dependence of the switching efficiency on the voltage changed with increasing the radiation energy density. For energy densities up to 0.2 J cm$^{-2}$, the switching efficiency monotonically decreased with increasing the electric field strength [Fig. 3, curves (*1*) and (*2*)], in accordance with expressions (1) and (2). In the interval of electric field strengths from 0.1 to 10 kV cm$^{-1}$, the switching efficiency decreased approximately by a factor of 2.5. As the radiation energy density was increased, the switching efficiency decreased with increasing the field strength only up to a threshold value and then drastically increased [Fig. 3, curves (*3*) and (*4*)], remaining further almost constant, i.e. the switch resistance became constant. However, as mentioned above, because the mobility of charge carriers in semiconductors decreases with increasing the field strength, the Ohm law is not valid and the resistance of the semiconductor increases [14–16].

The higher was the energy density, the lower was the threshold field strength at which the type of the dependence

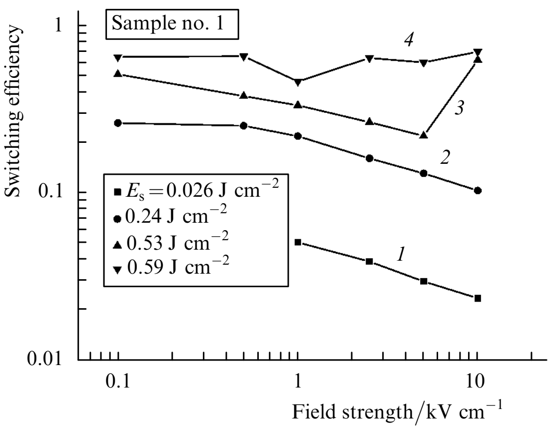

**Figure 3.** Dependences of the switching efficiency on the applied field strength for sample no. 1 for different 308-nm radiation energy densities.

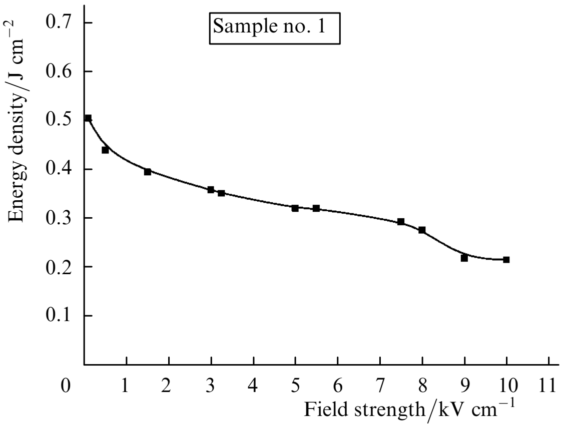

**Figure 4.** Threshold 308-nm radiation energy density, at which the breakdown of the sample no. 1 surface occurs, as a function of the applied field strength.

of the switching efficiency changes (Fig. 4). The 'ohmic' region of the switching efficiency corresponded to the breakdown regime on the crystal surface, which was reflected in current oscillograms [11, 12] and was observed visually [12].

The switching efficiency for sample no. 2 increases with increasing the applied voltage (Fig. 5); however, such behaviour in this case is not related to the surface breakdown. The oscillograms of current and light pulses almost coincided in the range of fields studied in the paper. The surface breakdown appeared only at high energy densities and field strengths (0.2 J cm$^{-2}$ and 50 kV cm$^{-1}$), which was observed in the current oscillograms. The necessary condition for the appearance of the surface breakdown was illumination of the side face of the sample. The breakdown was suppressed when a 2–4-mm aperture was mounted in front of the sample [12], as was recommended in [7].

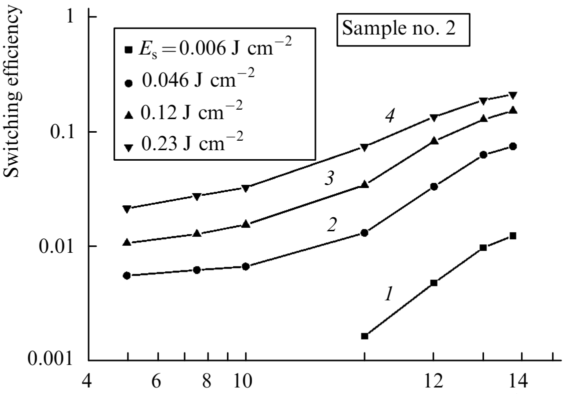

**Figure 5.** Dependences of the switching efficiency on the applied field strength for sample no. 2 for different 308-nm radiation energy densities.

The discussion of the voltage dependence of the switching efficiency for sample no. 2 is beyond the scope of this paper. Note only that the 'non-ohmic' behaviour of contacts to diamond is probably caused by their geometry, the method of their formation and material. As the applied voltage is increased, the switching efficiency saturates (Fig. 5). We assume that the switching efficiency achieves the maximum value with increasing the field and then decreases due to a decrease in the mobility of charge carriers.

## 5. Conclusions

Our study has shown that the use of a diamond switch in which UV radiation propagates orthogonal to the electric field strength vector (sample no. 1) reduces the switching efficiency approximately by a factor of 2.5 with increasing voltage to 1000 V. However, when UV radiation propagates parallel to the electric field strength vector (sample no. 1), the switching efficiency increases by an order of magnitude in the same voltage range.

At the energy density above 0.2 J cm$^{-2}$, the surface breakdown was initiated by UV radiation. The threshold radiation energy density required to initiate the breakdown decreases with increasing the electric field strength. Thus, the development of the surface breakdown in the diamond switch with the complete illumination of the interelectrode crystal surface (sample no. 1) restricts the range of operation voltages and radiation intensity. If the switch design allows the switch control without complete illumination of the interelectrode diamond surface (sample no. 2 with an aperture mounted in front of the illuminated surface), the operation voltage and intensity can be considerably increased due to prevention of the UV radiation-induced breakdown development.

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