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Breakdown studies of high voltage silicon and gallium arsenide photoconductive switches

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BREAKDOWN STUDIES OF HIGH VOLTAGE SILICON

AND GALLIUM ARSENIDE PHOTOCONDUCTIVE SWITCHES

by

Frank E. Peterkin

A DISSERTATION

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DISSERTATION TITLE

Breakdown Studies of High Voltage Silicon and Gallium Arsenide Photoconductive Switches

BY

Frank E. Peterkin

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GRADUATE COLLEGE
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BREAKDOWN STUDIES OF HIGH VOLTAGE SILICON AND GALLIUM ARSENIDE PHOTOCONDUCTIVE SWITCHES

Frank E. Peterkin, Ph.D.

University of Nebraska, 1995

Adviser: Frazer Williams

Silicon and gallium arsenide photoconductive switches are attractive choices for pulsed power applications which require low jitter, high speed operation. However, both of these materials exhibit breakdown modes which limit optical system efficiency.

Experimental results are presented on surface breakdown of high resistivity silicon in vacuum. Breakdown characteristics were measured for electric fields between 15 and 50 kV/cm across 1 cm silicon devices with heavily doped contacts in a parallel plate geometry. The first current rise signaling breakdown developed in as little as 25 ns after the field was applied. Simultaneous high gain streak and shutter photography showed the first visible emission appeared after the initial current rise. Visible spectroscopy revealed discrete emission lines with strongest components at 426.0 and 656.2 nm. A pressure increase of about $5x10^{-6}$ Torr occured for each breakdown event, with constituents at 12, 28, and 44 atomic mass units. Damage tracks 10 to 50 μm in diameter were seen with SEM and showed signs of filamentary current flow with melting. Breakdown could be inhibited by illumination with 1064 and 532 nm

laser pulses before application of the electric field. A model of silicon surface breakdown is presented which shows heating of conducting channels due to surface band bending or streamer propagation could lead to breakdown on the time scales observed experimentally.

Gallium arsenide exhibits a mode termed "lock-on" in which breakdown occurs after illumination. Measurements of the distribution of electric field in a GaAs switch utilizing the Franz-Keldysh effect are reported. Calibration measurements showed the validity of the measurement. Absorption images of a lateral geometry GaAs switch revealed electric field domains up to 50 kV/cm appearing only with laser activation. The number of domains and their field intensity increased with increasing applied field and laser intensity. Lock-on filaments developed normal to the direction of the domains, and tended to relax the electric field.

I was gratified to be able to answer promptly, and I did.
I said I didn't know......

Life on the Mississippi
by Mark Twain

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CHAPTER 1

Pulsed Power and Photoconductive Switching with Si and GaAs

1.1 INTRODUCTION

The most fundamental action required in electrical circuits of virtually every kind is switching, whether for changing logic levels in low voltage digital circuits, the distribution and control of electric power supplied by the local utility, the pulsed operation of radar systems, or simply the ubiquitous "ON-OFF" switches found on all electrical equipment. Each application requires different characteristics from the switching device in terms of control source, speed, size, repeatability, lifetime, rated switching voltage and current, etc. When choosing or designing a switch for a given application there will often be a trade-off of enhanced performance of one characteristic at the expense of reduced performance in another.

The area of electrical engineering known generally as Pulsed Power provides a good example of these statements. Pulsed Power is associated with the generation and application of pulsed electrical voltages and currents at very high levels. The range of operation of Pulsed Power circuits can be from kV to MV, with associated currents of kA to MA. Although the instantaneous power can be extremely high (as much as 10^{12} W) the total energy may not, since a pulsed power event generally occurs over relatively short time scales of typically ns to ms.

The most important element determining the performance of a pulsed power circuit is the switch. Fundamentally, a pulsed power circuit is very simple, consisting of an energy source, a switching device, and a load as shown in Figure 1-1. The energy source is typically an inductive or a capacitive storage system. An inductive system stores energy in the magnetic field of current flowing through an inductance and requires an opening switch to divert the energy to the load. A capacitive system stores energy in the electric field of a capacitance (either banks of capacitors or a dc charged transmission line) and delivers energy by the action of a closing switch.

Due to the maturity of closing switch technology compared to opening switches, most pulsed power systems are capacitive in nature and much attention is paid to refining the characteristics of high power closing switches. The switch device when in the off state must present a high enough impedance so that little or no voltage appears across the load. In response to a control signal of some kind the switch must then change to a low impedance such that most of the supply voltage appears across the load. After some time the load must be switched off again.

The following discussion emphasizes the characteristics which must be present in a pulsed power closing switch. Pulsed power circuits are often designed with a transmission line geometry to ensure fast rise times. This implies a characteristic impedance in the 10 to 100 Ω range for reasonable physical geometries. Thus the "high" impedance presented by the switch may only need to be in the kΩ range to satisfy the off condition. However, very high voltages might still force the required switch impedance to be much greater. For example, a 100 kV dc source applied to a 100 kΩ switch impedance would

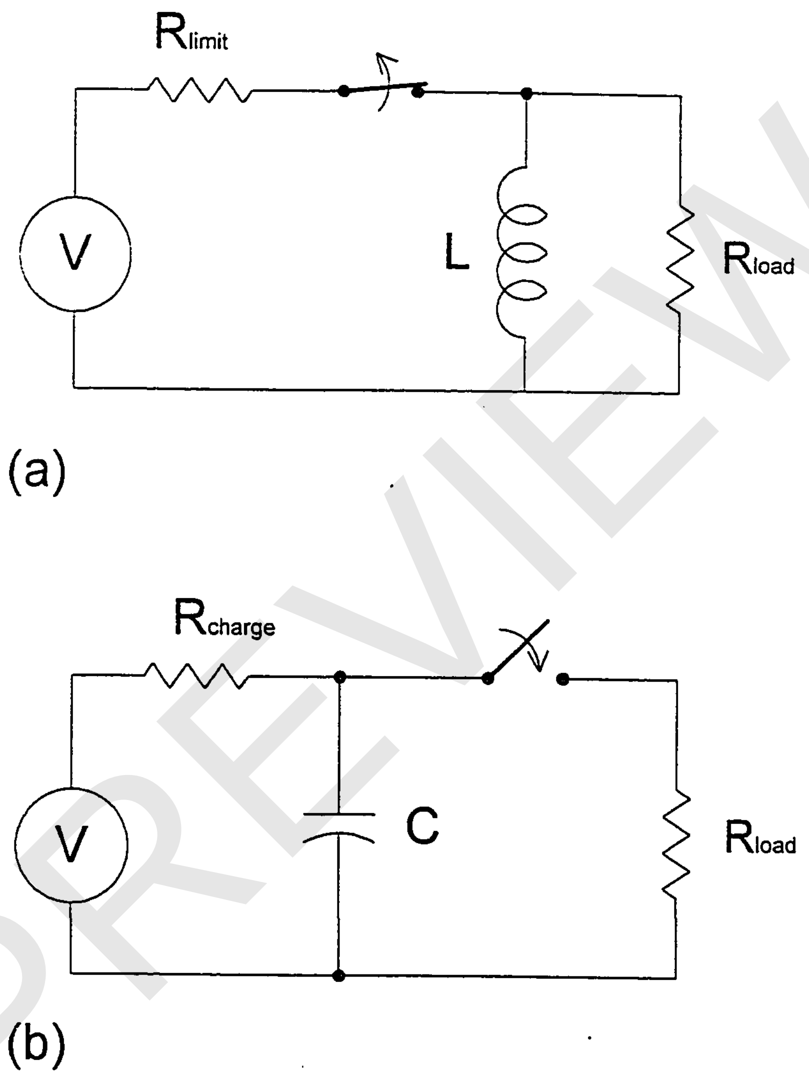

Figure 1-1 Schematic of typical pulse power systems. (a) Inductive systems store energy in the magnetic field of an inductor (L) then deliver power to the load when the switch opens. (b) Capacitive systems store energy in the electric field of a capacitance (C), and apply that voltage to the load when the switch closes.

dissipate 100 kW in the switch volume. Even though negligible power would be delivered to a 50 Ω load the power deposited in the switch would be unacceptable. Many pulsed power applications require essentially an open circuit simply to maintain switch integrity by avoiding power dissipation.

The control signal to turn on a pulsed power circuit may present problems related to isolation. Generally, a low-voltage control circuit is desired to trigger switch action. The possibility of high voltage feeding into the control circuitry presents a potential for both circuit damage and physical injury to human operators. Thus the control sections of pulsed power switches demand special attention.

The time required to change state from high impedance to low impedance should be as short as possible from the perspective of circuit rise time. Further, the OFF to ON transition is the time when maximum power is deposited in the switch volume, as shown schematically in Figure 1-2. This energy may cause physical damage to the switch or it may simply decrease the overall efficiency of the circuit by reducing the energy delivered to the load. Switch rise times are usually desired to be in the ns to μs time scale, although ps switching is becoming of more widespread interest.

There is usually a delay between the application time of the control signal to initiate switching and the actual time at which the switch closes. This delay time is important for several reasons. It may be that the pulsed power circuit is responding to some external event, so that a short turn-on delay is required for the circuit to carry out its function (a crowbar circuit which shorts out another circuit is an example). More often it is the “jitter” or variation in the time between application of the trigger signal and switch closure that is of concern. A low value of jitter means that the delay time is consistently the same. The jitter

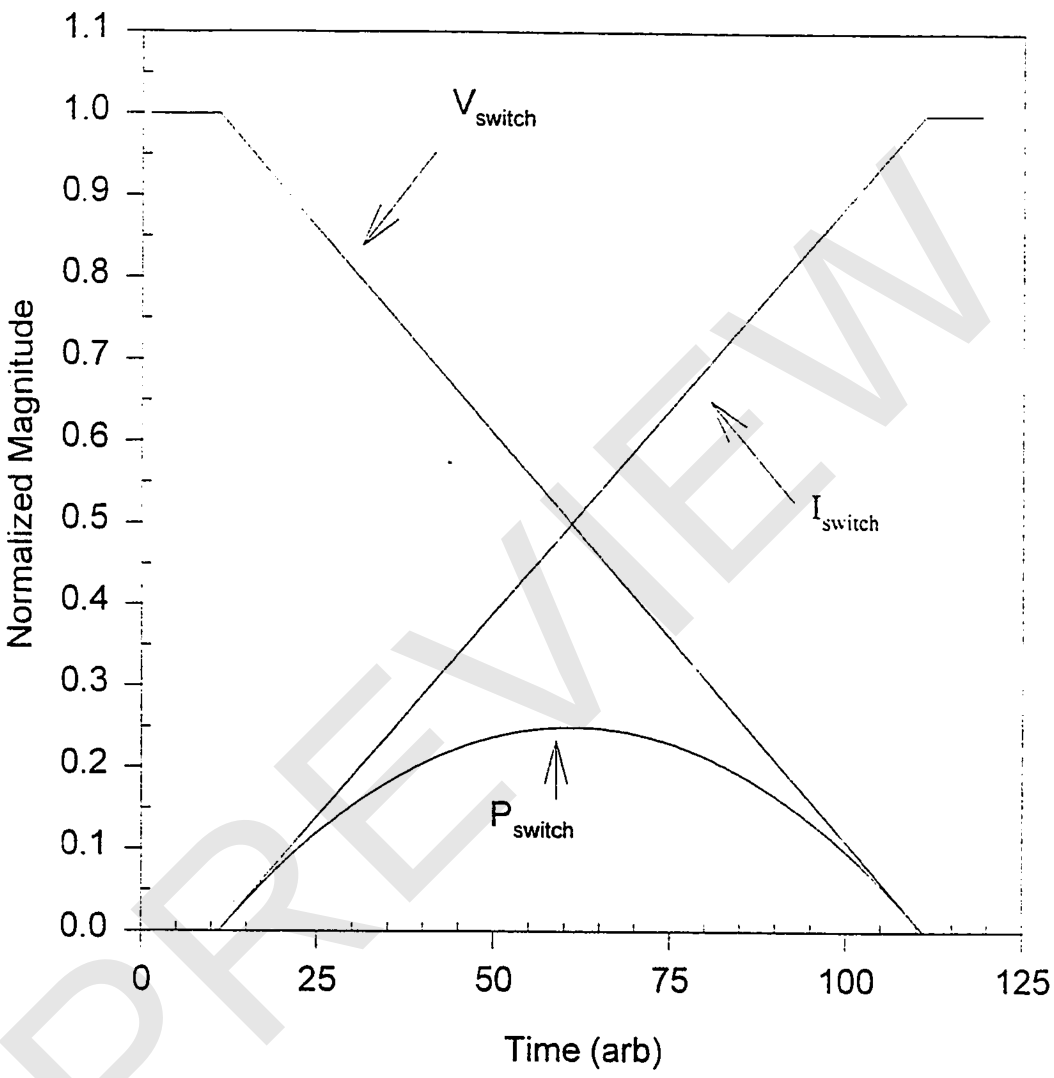

Figure 1-2 Normalized plots of switch voltage, current, and the power deposited in a switch during the closing transition.

of photo-conductive switches is limited by the activating laser system and can be in the ps range. By comparison, arc and discharge switches often have jitter on the order of 1 ns or more[1].

Pulsed power circuits operating at high power imply low values of circuit impedance ($P=V^2/R$) , often in the 10 to 100 Ω range. On-state switch impedances must usually be much less than 1Ω, therefore, to ensure efficient energy delivery to the load.

Finally, the circuit must be turned off. This typically means waiting until all the energy has been transferred from the capacitive storage medium to the load. Pulsed power systems are often operated in this manner. Thus a Marx bank will generate exponential decay pulses with pulse widths controlled by the circuit RC time constant. A dc-charged transmission line will present a very clean and square pulse if the switch rise time is short compared to the typical propagation delays in the circuit and closes into a load with matched impedance. The pulse length will be given by twice the propagation time of an electromagnetic wave down the length of the transmission line. It is also possible to actively turn off a circuit with an opening switch like the BOSS switch discussed below.

1.2 Switch Types

There are many types of closing switches used in pulsed power circuits, but they can generally be lumped into two categories, those in which the switching action is the result of electrical breakdown of an insulating medium and those which do not. The first category includes the most often used switches; spark gaps, discharge switches, and vacuum tubes. The second category consists primarily of solid state semiconductor switches.

Spark gap switches come in many varieties[1]. For low voltage applications (usually <10 kV but as high as 40 kV) low pressure switches like thyratrons, crossatrons, and pseudosparks operate in a diffuse discharge mode and display relatively high repetition rates (kHz at low voltages, 100's of Hz at the high end) and have operating lifetimes up to 10^9 shots[1,2]. For applications requiring greater than 10's of kV or kA, high pressure electrode or laser triggered spark gaps are usually used[3]. These switches depend on the formation of an arc in an insulating dielectric separating primary electrodes. The dielectric may be a gas, liquid, or solid, with gaseous by far the most common.

Spark gaps meet many of the primary requirements for pulsed power switches. They offer an open circuit in the off state due to the insulating properties of the dielectric. They can be triggered in a variety of ways, including optical triggering with high power lasers and electrical triggering with field-distorting control electrodes. When the arc is formed, the impedance is very low and the arc is sustained as long as current flows in the circuit. Thus turn-off with spark gap switches is generally passive, although it is possible to add another switch across the load so that the circuit is turned off by shunting the current away from the load.

The disadvantages of spark gap switches have to do with lifetime, rise time, jitter, repetition rate, and operating range. The repeated action of an arc on switch electrodes eventually causes surface damage due to the high current density at the arc-electrode contact. This damage changes the switch operating characteristics and thus requires frequent service. Rise time and jitter in the ns range can be achieved, but the arc formation times limit any further improvement and again these characteristics drift as electrodes degrade. Dissipation of the remaining arc channel takes time, during which the switch is unable to hold off

the full supply voltage. The repetition rates of spark gap switches are typically limited to a maximum of a few hundred Hz as a result. Finally, spark gaps usually work well only in a narrow range of voltage near the self-breakdown limit of the gap and must be adjusted by changing the gas pressure or electrode spacing to operate at a different voltage.

Solid state switches offer different advantages and disadvantages relative to spark gap switches. For voltages of the order of 1-2 kV, there are high voltage devices like MOS transistors, SCR's, thyristors, IGBT's, and MCT's, which offer all the benefits typically associated with solid state circuitry: speed, lifetime, repeatability, circuit board integration, etc.[4]. These devices can sometimes be stacked to switch higher voltages, but the cost in circuit complexity and performance starts to mount. At higher voltages a photoconductive switching arrangement becomes attractive.

Figure 1-3 shows a schematic diagram of a typical pulsed photoconductive switch (PCS) system. It consists of a piece of high-resistivity semiconductor material (typically Si or GaAs) which interrupts the conducting path between a pulsed or dc biased high voltage source and a load, all connected in a transmission line geometry for fast rise time characteristics. Energy is switched into the load by illuminating the semiconductor material with visible or near infrared light, generating electron-hole pairs in sufficient numbers to drop the switch resistance well below the characteristic impedance of the system.

A PCS can be constructed in several geometric and electrode configurations, as shown in Figure 1-4. The most common forms are the bulk (Fig. 1-4 a, b) and lateral (Fig. 1-4 c, d) geometries. In the bulk form, contacts are placed on the ends of a large piece of semiconductor and

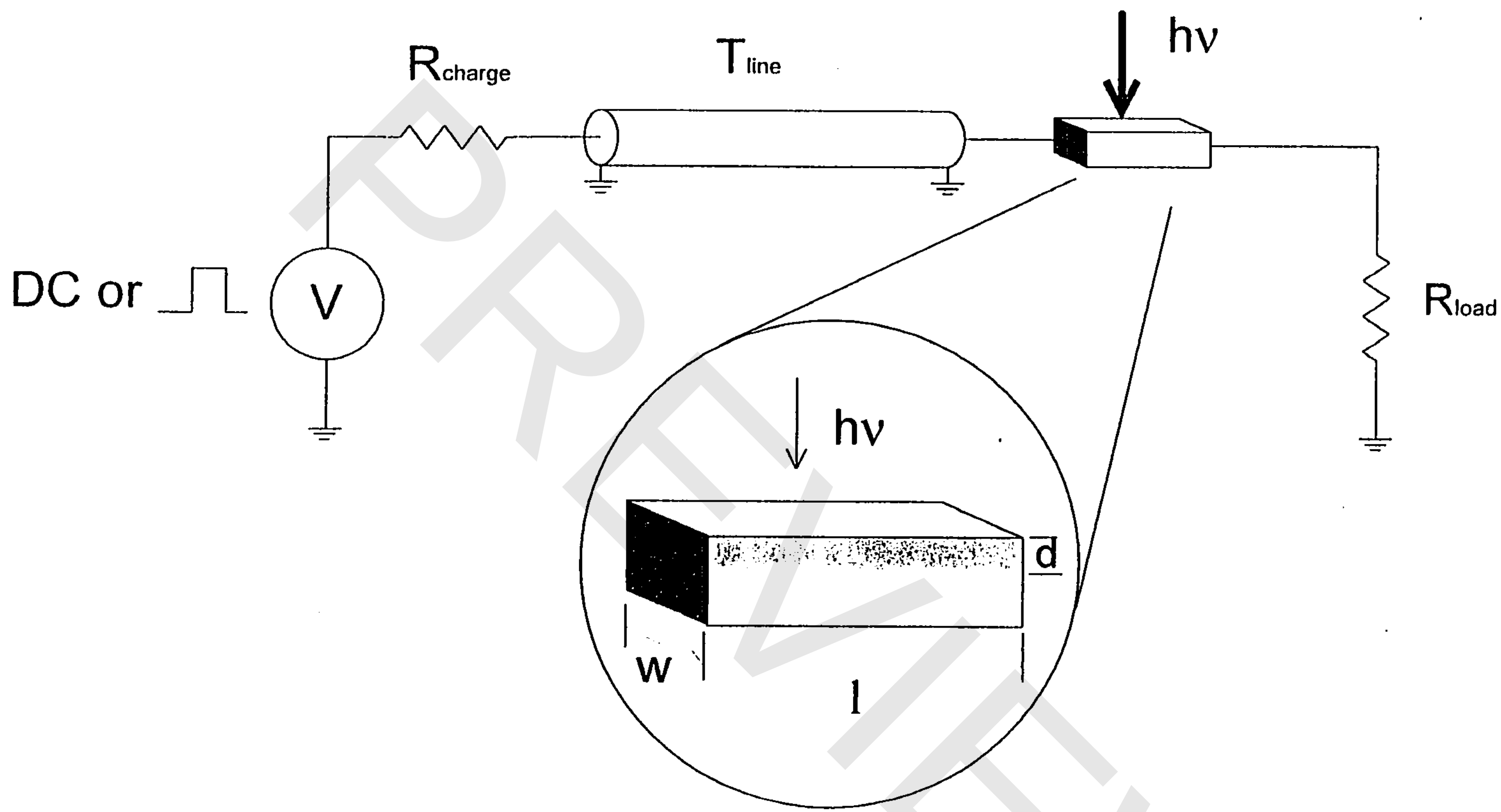

Figure 1-3 Typical photoconductive switch circuit arrangement. The inset illustrates that the switched volume is not necessarily the total material volume since the penetration depth of the light, d, may be less than the material thickness.

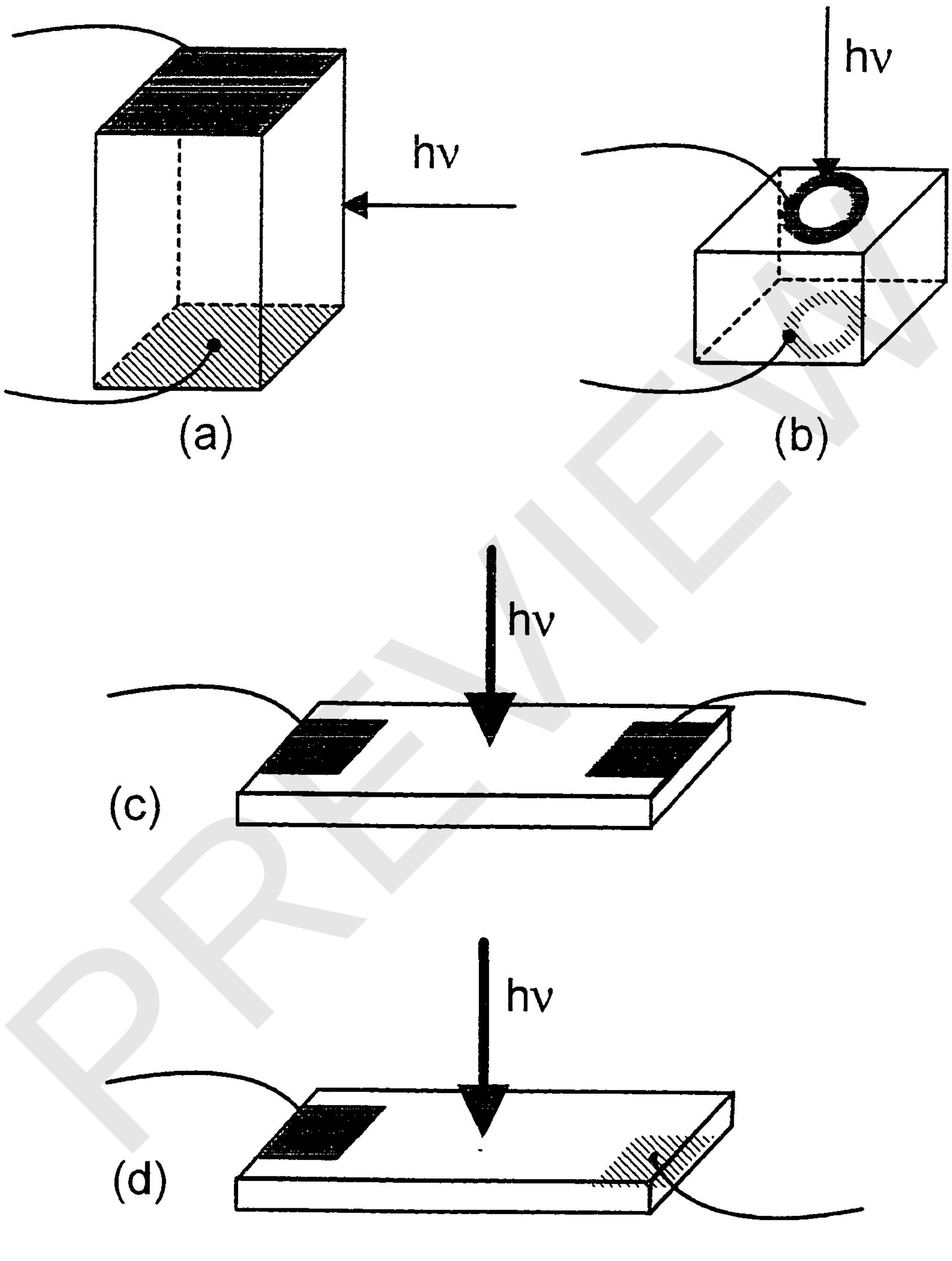

Figure 1-4 Typical photoconductive switch configurations - (a) bulk with end contacts and side illumination, (b) bulk with transparent or open contacts and end illumination, (c) lateral with same side contacts, (d) lateral with opposite side contacts.

illumination enters from one or more sides. The lateral geometry consists of contacts placed on the same side of a semiconductor wafer with illumination entering from the contact side, the back side, or both. The lateral geometry is more suitable for production line processing and inclusion in fast, stripline geometry systems. The other configurations shown in Fig. 1-4 are variations which increase surface flashover resistance or offer different switching options. (e.g. illumination through a transparent contact).

Any semiconductor may be used in a PCS, but Si and GaAs are generally the materials of choice. Silicon is well understood, readily available in nearly intrinsic form, simple to handle and process, and matches well with the available optical sources. However, the intrinsic resistivity of silicon is only about 50 kΩ-cm at room temperature, so a silicon PCS must be either pulse biased or cooled to avoid thermal runaway. Semi-insulating GaAs can be obtained with resistivity made as high as 10^8 Ω-cm by proper impurity compensation. This makes GaAs very attractive as a PCS with dc biasing. Doping with other deep level impurities also allows GaAs to be used in a bistable switching arrangement, as discussed in section 1.4 below.

PCS systems offer many advantages over conventional spark-gap type closing switches. If the switch is uniformly illuminated over its surface, turn-on time is only limited by the speed with which the required number of photons can be delivered to the semiconductor volume. Since turn-on time is not related to the applied voltage across the semiconductor, the switch operates identically for any voltage below the rated maximum. The bulk nature of the current flow in the semiconductor has lower inductance when compared to the filamentary arc channel in spark-gaps, and thus rise time is limited more by the external circuit. The conduction or on-time of the switch is determined by the recombination time