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Current state of photoconductive semiconductor switch engineering

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ABSTRACT

This paper presents the current state of a photoconductive semiconductor switch engineering. A photoconductive semiconductor switch is an electric switch with its principle of operation based on the phenomenon of photoconductivity. The wide application range, in both low and high-power devices or instruments, makes it necessary to take design requirements into account. This paper presents selected problems in the scope of designing photoconductive switches, taking into account, i.e. issues associated with the element trigger speed, uniform distribution of current density, thermal resistance, operational lifespan, and a high, local electric field generated at the location of electrodes. A review of semiconductor materials used to construct devices of this type was also presented.

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1. Introduction

A PCSS (*Photoconductive Semiconductor Switch*) is an electrical switch with its operating principle based on the phenomenon of photoconductivity. When compared to classic switches, PCSSs are characterized by better properties including, i.e. optical coupling of control circuits, compact geometry, low switching jitter, faster rise and fall times, lower inductance, high switching frequency [1]. PCSSs are made with the use of highly-resistivity semiconductor materials. Depending on the used photoconductive substrate and the design of the switch itself, the operating voltage of an open switch may reach 100 kV and the forward current might be in the range of 1 kA [2], hence, these switches may find their application in high energy processing instruments, including directed energy pulse generators for HPEM (*High Power Electromagnetic*) weapons.

The wide application of the switches, in both low and high energy devices or instruments, make it necessary to consider, i.e. operating conditions. The property, important in low-energy applications, in information processing and control systems, will be the speed of the element triggering, as well as minimization of its dimensions, while in the case of high-energy applications – uniform current density distribution in the switch and its thermal resistance. The parameters of such devices depend on a number of physical phenomena occurring during its operation, which in turn limit the possible switch performance. The paper presents the operating idea of a photoconductive switch, supplemented with a review of semiconductor materials used as a substrates for

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such devices. Furthermore, we present selected issues in the scope of designing of photoconductive switches, extended by methods enabling the limitation of their negative impact on the operation of PCSSs, hence, improving output parameters of the devices.

2. Switch design and operating mode

PCSS is made of a semiconductor material with metal contacts placed on it which enable connecting the material to an electrical circuit. The area between the contacts is called a switch gap. The idea of operation of such a device and an example of a photocurrent path are presented in Figs. 1 and 2, respectively. The switch is excited by an optical signal, with energy higher than the bandgap energy of a given material, resulting in an increase in charge carriers concentration which causes a decrease in the semiconductor material resistivity, even by several orders of magnitude. In practice, the switch can be of various geometry which indirectly impacts the operating parameters of the entire device. As a consequence, the thickness of the switch should be equal to or higher than the depth of optical absorption, in order for the entire optical energy to be absorbed by the semiconductor material. The length of the switch depends on dielectric strength of the semiconductor material while its width is determined by the maximum current density. In addition, the switch geometry is also dependent on the method of an optical signal input to the device and the photoconduction operating mode used.

PCSS may operate in two modes: linear and non-linear. In a linear (conventional) mode, one absorbed photon generates one electron-hole pair. After lighting is switched off, thermal emission processes of carriers from deep defect centres take place, as well as recombination processes of charge carriers which recover the properties of the semiconductor material to the state prior to illumination. Within this mode, charge carriers are generated on the basis of intrinsic absorption (direct, bands-related) or extrinsic absorption (indirect, dope-sites-based). Photon penetration depth depends on the absorption factor of the used semiconductor material for the adopted wavelength and may reach tens of microns for direct transitions and a few microns for indirect transitions. In the case of intrinsic absorption, level the optical energy can reach is very small – in the range of tens of microns. As a result, optical energy density should be in the order of a few mJ/cm^2, so that it can lead to a reduction in the switch resistance. As a consequence, switches of this type are most often designed in side geometry as shown in Fig. 1b) [2]. In the case of extrinsic absorption, the optical energy may penetrate very deep areas, depending on the used dopants and their concentration. This operating mode allows designing (matching) the optical signal penetration depth, hence dimensions of conductive areas of the switch, via controlling concentration of dopants introduced into the semiconductor. Moreover, absorption of this type provides possibility to select the wavelength of incident light.

Excitation in the linear mode is independent of a value of the electric field generated along the switch. As a consequence, a PCSS may operate in only low-voltage circuits (electric field strength lower than 4 kV/cm). The switch current is largely concentrated on the surface of the semiconductor and surface flashover limits the maximum voltage at which a device may operate. Linear photoconductive switches are characterized by a longer operational lifespan, due to a decreased current density [2].

The non-linear mode, also called avalanche or high gain mode, occurs at a higher electric field. Charge carriers, excited by illumination, when present in a strong electric field gain additional kinetic energy and punch outer electrons into the conduction band which is called impact ionization and, as a consequence, manifests itself with an avalanche-type generation of charge carriers in the semiconductor material. It means that a photon may generate more than one charge carrier. An initiated avalanche process of charge carriers multiplication is continued until the moment, in which the field along the switch falls below a certain threshold, depending on the used semiconductor material (e.g., 4–6 kV/cm for GaAs). In this mode, the laser acts only as a trigger. If the electric circuit is able to provide the switch with sufficient power, it remains in the activated state, even after the laser pulse stops. As a consequence, this mode occurs only under a strong electric field along the switch.

The requirements regarding the pulse energy, in the case of a device operating in linear mode, were referred to earlier. In comparison, avalanche-based switches require smaller trigger pulse energies than linear-mode switches. For example, a linear PCSS, operating at 100 kV, in order to gain a resistance of 1 Ω in the closed state, requires a trigger light impulse with an optical energy equal to 25 mJ, while an avalanche switch, the energy equal to only 90 nJ ($1\ J = 0.62415 \times 10^{19}$ eV). As a result, one photon in an avalanche switch may generate 100,000 times more charge carriers than in the same switch operating in a linear mode [3].

3. Application

The PCSS technology is being developed mainly due to the possibility of using this type of devices in many applications. Basic features creating the current wide interest in PCSS elements are the possibilities of their fast triggering (in the range of few nanoseconds) which is why they find their application in analogue-to-digital converter circuits, control and guiding systems. They can also be used in microwave and terahertz signal generators which operate under the direct conversion from direct current (*DC-RF*) [4]. More and more often switches are becoming basic elements in power electronics.

One of the examples of PCSS application is a hybrid power switch (Fig. 3) which consists of the fast mechanical switch Z_1 and a semiconductor power PCSS switch. The PCSS switch is attached to the fast switch Z_1 in parallel. This construction of the hybrid switch enables the fast switch to be closed on any moment of the voltage occurring between *a* and *b* terminals synchronously with the supply voltage. Properties of the described hybrid switch are similar to properties of an ideal switch. They ensure electric-arc-less switching at a minimal contact resistance in the on state and a visible insulation break in the off state.

PCSS are used with the purpose to increase efficiency of the device and switching dynamics, as well as values of currents and voltages. Advanced switching devices with a long operational lifespan will be crucial elements for LTD (*Linear-Transformer-Driver*) in next generation accelerators. Devices of such type use large amounts of switches [5,6]. Another application may be forming programmable pulse systems for dynamic material testing (Z-next, Genesis, THOR), efficient pulse systems for biofuels, short pulses (10 ns) for the Defence Threat Mitigation Agency (HPEM) and sprytron (fast-arc high-voltage and high-current switch) in nuclear weapons [7].

An interesting solution, widely described in the literature, is a compact semiconductor system, which is one of the main trends in the development of pulsed power technologies. It is inseparably associated with designing a perfect switch for application of this type. An example is a compact high-voltage pulse generator. It was constructed for use in a particle accelerator DWA (*Dielectric Wall Accelerator*) [8]. Accelerators of this type are a chance for next generation devices used in X-ray radiography and proton therapy. Such a device enables the acceleration of protons to high velocities and directing their beam inside the body of a patient. Each DWA module consists of semiconductor planar Blumlein lines SPTL (*Solid-state Planar Transmission Lines*), PCSS, laser diode operating as a trigger,