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A bulk optically controlled semiconductor switch

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Turn-on and turn-off of bulk semiconductor switches, based on excitation and quenching of photoconductivity, respectively, have been demonstrated with copper-doped II-VI semiconductor crystals. The increase of the conductivity (turn-on) was realized with a xenon flash-lamp pulse of 15-μs duration. A reduction of the conductivity (turn-off) was obtained by irradiating the samples with IR light using an 8-ns Nd:YAG laser pulse (YAG denotes yttrium aluminum garnet). For turn-on in CdS:Cu the conductivity follows the xenon flash excitation. The turn-off time constant was 250 ns. ZnS and ZnSe crystals showed a slower response. A memory effect for the IR light was observed.

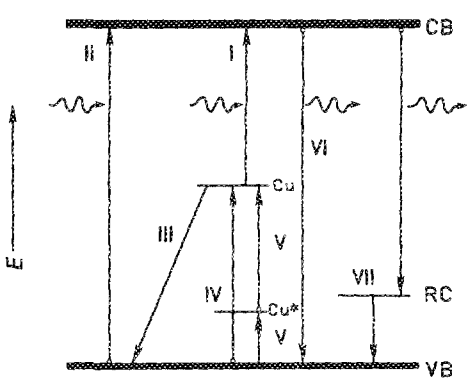
INTRODUCTION

Turn-on and turn-off of photoconductive semiconductor switches can simply be obtained by turning the radiation source on and off, respectively. For semiconductors with rapid carrier recombination, such as Cr-doped GaAs, it is possible to produce photoconductivity responses with picosecond precision.[1] Rapid carrier recombination, desirable for fast turn-off, however, means there is a large carrier loss rate also during the on state, which must be compensated for by means of photons. The necessity for using a high-intensity light source to keep the switch closed limits the application of this method to the generation of pulses in the nanosecond and subnanosecond range, corresponding to the pulse length of high-power lasers. Turn-on and turn-off of semiconductor switches with long recombination lifetimes by using two subsequent laser pulses have been reported by Johnson and Auston[2] and by Platte.[3] In both cases, the turn-off with the second delayed laser pulse was based on the photoexcitation of a different region of the semiconductor switch. This excitation opened a new path for the current, thereby short circuiting the previous current path.

A concept for optically controlled turn-on and turn-off that is based on excitation and quenching of photoconductivity in the same semiconductor volume has been previously introduced by Schoenbach *et al.*[4] These bulk-controlled switches promise to have very attractive features for applications in pulsed power systems. They can be turned on and off on a submicrosecond time scale, they should be able to handle current densities in the kA/cm^2 range, and they are bistable, which means that they need control power only for turn-on and turn-off, not to sustain the on state. They do not have depletion layers; the excitation and quenching of photoconductivity occur uniformly in the entire bulk of the semiconductor. All these features make bulk optically controlled semiconductor switches (BOSS) strong competitors for commonly used high-power switches, such as thyristors, thyratrons, and spark gaps. Other applications for these "bistable" switches are in the area of low-power memory devices.

The concept of optical control of bulk semiconductors is based on photoionization of deep levels to increase the conductivity—turn the switch on—and stimulated recombination of electrons and bound holes in the traps to turn the switch off. In order to prove the feasibility of this concept, optical experiments with semiconductors of the II-VI group were performed. The semiconductor that was mainly used was cadmium sulfide (CdS) containing copper (Cu) and some other "natural" defects. It is known that the conductivity of CdS:Cu can be stimulated with the light of photon energy larger than $h\nu > 1.27$ eV and that additional illumination can quench the photosensitivity.[5] Maxima of desensitization are at $h\nu = 1.2$ eV and $h\nu = 0.85$ eV.[6]

Figure 1 shows the energy diagram for CdS:Cu with possible transitions. The increase of conductivity (turn-on)



CB: conduction band
VB: valence band
RC: recombination center
Cu: copper impurity ground level
Cu*: copper impurity excited level

Arrows point in the direction of electron transition.

FIG. 1. Electronic levels in CdS:Cu with transitions which determine the switching behavior.

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can be obtained by direct electron excitation from the trap for $h\nu > 1.27$ eV (I), band-band excitation (II) for $h\nu > 2.45$ eV, and hole trapping (III). The optical desensitization (turn-off) is realized by electron-hole recombination (VI), stimulated by hole excitation from the trap (IV), which is possible with $h\nu > 1.18$ eV, and through a two-step excitation with $h\nu = 0.85$ eV via a Cu impurity level (V). The band-band recombination rate can be increased by recombination centers (VII).

EXPERIMENTAL SETUP

In order to demonstrate the feasibility of the optical switch (BOSS) concept, an experimental setup as shown in Fig. 2 was used. The semiconductor switch was turned on by illuminating the sample using a xenon flash lamp. The rise time of the flash was 8 μs, and its half-width was 15 μs. This "white-light" excitation causes direct ionization of traps as well as band-band electron-hole pair generation. Holes in the valence band can be trapped at Cu and "natural" impurities. Ionized impurities can subsequently catch electrons that were excited from the valence band. This recombination limits the switch sensitivity as shown in (Ref. 4), where this effect is considered as two-step photoexcitation and subsequent recombination.

The reduction of conductivity (turn-off) is obtained by irradiating the semiconductor with laser light of wavelength 1064 nm [Q-switched Nd:YAG laser (YAG denotes yttrium aluminum garnet)] at a pulselength of 8 ns. The laser is triggered 5 μs after ignition of the xenon flash using a double-pulse generator. The infrared light can excite electrons from the valence band into ionized "natural defects" and Cu-impurity levels (transitions IV and V), but it is not possible to use it for the excitation of electrons to the conduction band.

In order to study the performance of a variety of semiconductor crystals, simple contacts were used. Instead of evaporating ohmic contacts on each sample, an electrolytic $CuSO_4$ water solution was used to realize electrodes. The samples were biased at 20-V dc and the current was measured with an impedance-transforming amplifier (rise time

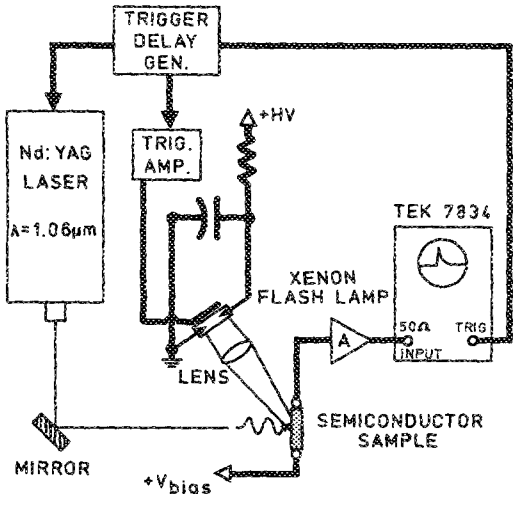


FIG. 2. Experimental setup.

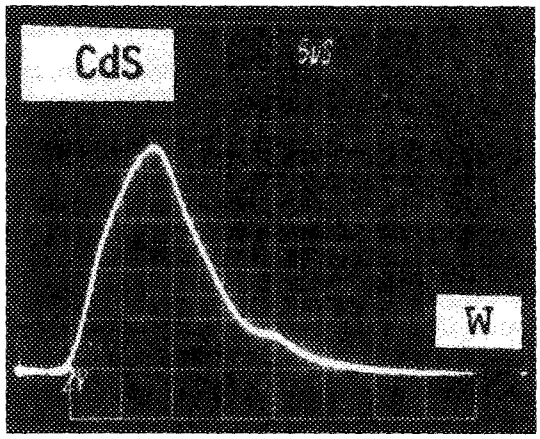


FIG. 3. Photocurrent response of a "fast" CdS:Cu crystal to the xenon flash pulse.

< 10 ns) to match the 50-Ω input impedance of the oscilloscope (Tektronix 7834).

EXPERIMENTAL RESULTS AND DISCUSSION

The turn-on response of the various "white-light"-irradiated semiconductor samples followed the temporal emission characteristic of the xenon flash lamp. However, for different samples, the sensitivity varied by an order of magnitude and the decay time of the semiconductor conductivity varied between nanoseconds and microseconds. The temporal response of a "fast" sample is shown in Fig. 3. It resembles the light emission of the flash lamp. The turn-off response of the semiconductor showed strong differences for different samples. Some samples did not show any turn-off effect.

The typical response of a "good" sample to irradiation with white light and subsequent illumination with IR light is shown in Fig. 4. The upper trace shows the turn-on phase

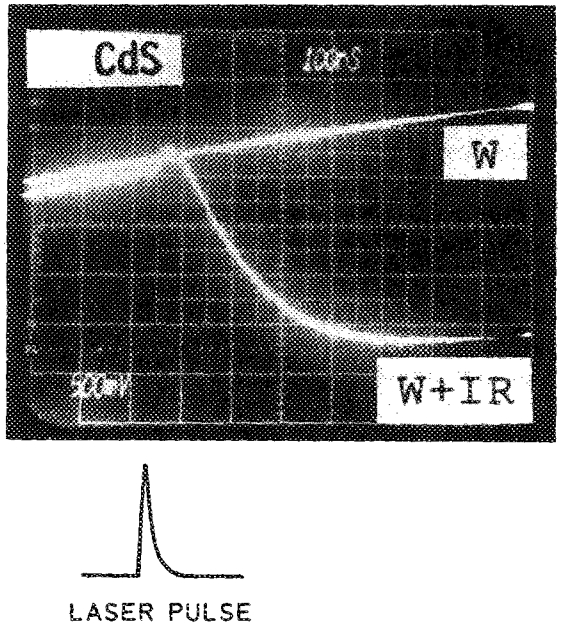


FIG. 4. Turn-on (upper trace) and turn-off (lower trace) response of a CdS sample.

only. The lower trace depicts part of the turn-on phase (left) and the turn-off phase. The laser pulse at first stimulates additional conductivity for a time of about 50 ns due to the generation of free holes (transitions IV and V) and then the conductivity decreases due to electron-hole recombination.

The time constant for this decay, which in this case was 250 ns, varies drastically for different samples. Some samples which contained Cu, evident by IR Cu luminescence, did not turn off at all, while with samples containing vanadium (Va) in addition to copper the best turn-off results were obtained. This result is in agreement with considerations that electron-hole pair recombination centers improve the turn-off characteristic of the switch.[4]

A reduced conductivity of the semiconductor samples long after they were illuminated with IR light was observed even when the white-light excitation was still present, as shown in Fig. 5. This behavior can be explained by the existence of several deep centers above and below the Fermi level. Under equilibrium conditions only traps below the Fermi level are filled with electrons. The laser pulse creates much more holes than needed for direct recombination with the free electrons, generated by the xenon flash. Some of the holes are stored in shallow traps, while some of the electrons are trapped in energy levels above the Fermi level. The free electrons produced by the continuous white-light irradiation after laser turn-off can recombine with the trapped holes, an effect which reduces the photosensitivity of the semiconductor. This recombination can take place until the trap system is in equilibrium again, which may take seconds or minutes in II-VI semiconductors at room temperature.

The influence of the intensity of the white light on the photosensitivity of CdS after IR irradiation is shown in Figs. 6(a) and 6(b). They show the photocurrent with "white" illumination only (upper trace) and "white" light and laser illumination (lower trace). In Fig. 6(a) the intensity of the xenon flash was eight times the intensity used to get the result shown in Fig. 6(b). In the first experiment [Fig. 6(a)] more free electrons were generated than trapped holes were available for recombination; in Fig. 6(b) the switch stayed in the off state. Because of the smaller electron generation rate, all electrons that were generated after the IR laser pulse found holes for recombination.

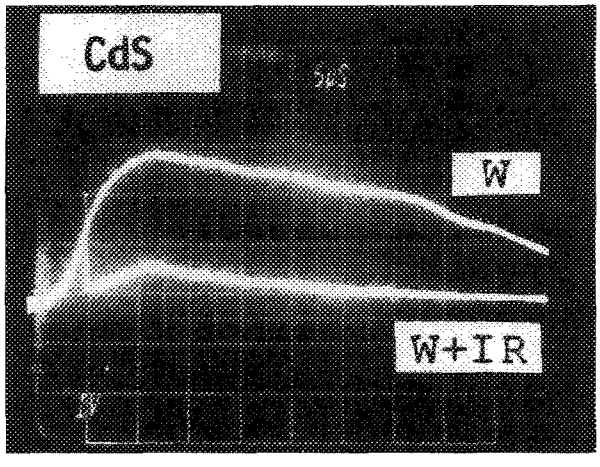
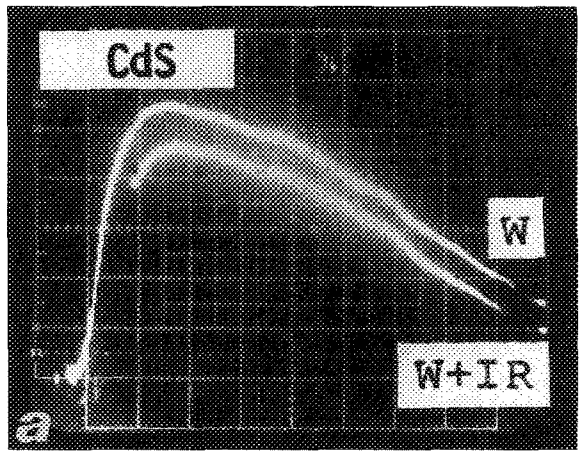


FIG. 5. Reduced photosensitivity after IR illumination.



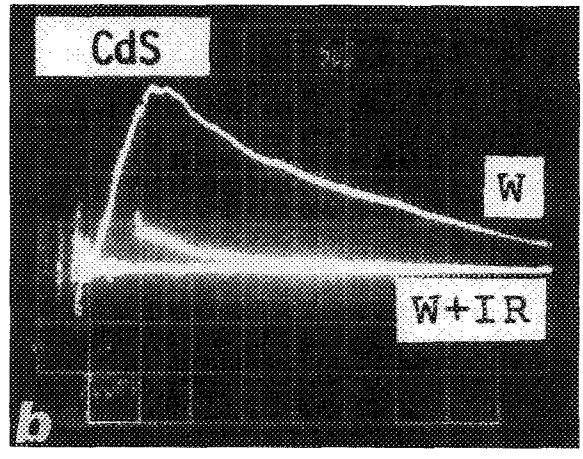


FIG. 6. Turn-off response to the same IR pulse, but for different turn-on intensities ("white" xenon flash). The white-light intensity in (a) was eight times the intensity in (b).

Similar experiments as in CdS have been performed with ZnS:Cu, ZnO:Cu, and ZnSe:Cu. Samples of ZnO:Cu showed a minor response to "white"-light excitation compared to CdS:Cu and no response to subsequent IR illumination. This is not surprising, considering the energetic position of the Cu level in this semiconductor (Table I). ZnS:Cu showed photoresponses as shown in Fig. 7, and the photoresponse of ZnSe:Cu is displayed in Fig. 8. In ZnS-Cu (Fig. 7), illuminated by the xenon flash and subsequently by the IR laser, the conductivity generated by the IR irradiation is higher than that for just white-light illumination for about 10 μs following the laser pulse. The decay time ($1/e$ value), however, is shorter (10 μs) for the double-illumination case than for the case with white light only (20 μs). In ZnSe:Cu (Fig. 8), the IR stimulated reduction of the conductivity is only a 10% effect, but the decay of the photocurrent after the laser irradiation is very fast and shows a nonexponential behavior. This is obviously due to the recombination of free electrons with free holes, whereas for white-light illumination the reduction of conductivity is caused by trapping of free electrons, resulting in an exponential decay.

According to the energy level data, ZnSe should be the best switch material in the group of direct semiconductors listed in Table I. The Cu level is much closer to the valence band than to the conduction band, which guarantees a good

TABLE I. Energy level data and mobilities of the investigated II-VI semiconductor crystals.

	CdS	ZnO	ZnS	ZnSe
Band gap (eV)	2.45	3.2	3.75	2.7
Cu-level (eV)	1.18	3.0	1.3	0.75
Cu-transition internal (eV)	0.85	0.85	0.95	unknown
Electron mobility at 300 K ($cm^2 V^{-1} s^{-1}$)	330	200	200	500
Hole mobility at 300 K ($cm^2 V^{-1} s^{-1}$)	43	180	12	28

spectral selectivity for the turn-on and turn-off process, as described in Ref. 4. Furthermore, ZnSe has a high electron mobility and a relatively small hole mobility, required for a high conductivity in the on state, and a small overshoot when turned off by IR generation of holes. However, as the experiment has shown, the recombination rate is too small to obtain an effective turn-off.

The Cu-level position in ZnO:Cu promises, similar to that in ZnSe:Cu, a good spectral sensitivity for the turn-on and the turn-off mechanism. It also has reasonable mobility values, but again the recombination rate is too small to make it a fast and efficient switch. In CdS:Cu the position of the copper level is too close to the middle of the band gap to get a reasonable spectral turn-on and turn-off sensitivity, especially at room temperature and taking phonon processes into account. The two-step process via the internal excited Cu state, which was used to generate holes, is inefficient compared to the direct photohole excitation in ZnSe. Nevertheless, because of their good recombination behavior CdS samples are superior to the other samples where switching application is concerned. Discrepancies between the experimental results and the predictions from the simple model discussed in Ref. 4, e.g., the turn-off pulse memory (Figs. 5 and 6), can be attributed to the existence of additional deep levels. While the presence of deep levels acting as charge traps limits switch speed and efficiency, levels which serve as recombination centers are important for fast turn-off.[4]

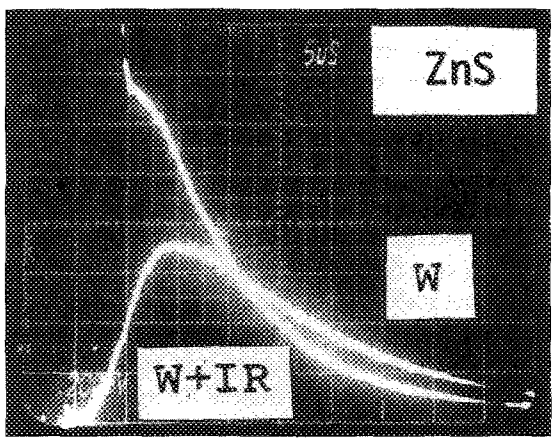


FIG. 7. Switch behavior of ZnS:Cu. The upper curve was obtained with white-light excitation only, the lower curve with additional IR illumination (laser pulse).

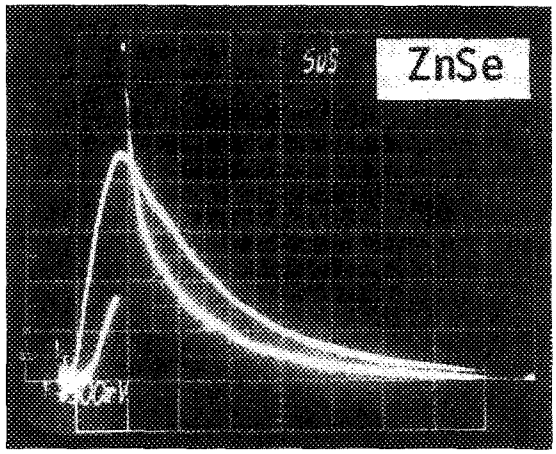


FIG. 8. Conductivity response of ZnSe:Cu. The conductivity of the crystal decays exponentially if excited with white light only (upper trace); it decays nonexponentially after additional IR illumination (lower trace).

Because of the low concentration of Cu in our semiconductor samples, no noticeable attenuation of the laser beam was observed. In order to obtain optimum, uniform hole excitation in the semiconductor switch, the Cu concentration should not exceed the value $(L\sigma)^{-1}$, where L is the dimension of the crystal in the direction of the laser beam, and σ is the photoionization cross section for holes from the Cu-impurity level. For CdS:Cu at room temperature, the value of σ is about 2×10^{-18} cm^2.[7] For a CdS:Cu crystal of 1 cm length, the Cu concentration should therefore be less than 5×10^{17} cm^{-3} for uniform excitation.

CONCLUSIONS

The experiments demonstrate the feasibility of the BOSS concept. They show that submicrosecond turn-off of photocurrent is possible in bulk semiconductor materials containing certain impurities, such as copper. The experimental results are in qualitative agreement with modeling results.[4] The difference in the ionization energy and the absorption cross section for electron and hole photoionization is important for the selective generation of both charges and therefore determines the turn-on and turn-off behavior. In CdS, where the Cu level is close to the middle of the band gap, a two-step excitation via an excited impurity level can be used for hole generation. The rate of recombination of free holes with free electrons determines the turn-off speed and efficiency. It can be enhanced by doping the base material with impurities which create recombination centers. A higher mobility of electrons than of holes improves the ratio of switch-on to switch-off conductivity. The existence of additional trap levels, not considered in the model of Ref. 4, causes a strongly reduced photosensitivity after turn-off in some of the samples. This might limit the frequency of repetitive switching if the light intensities for the turn-on and turn-off phase are not carefully matched.

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