Ultrafast optoelectronic ferromagnetic semiconductor CdCr$_2$Se$_4$ switch

Ardie D. Walser and R. R. Alfano
Institute for Ultrafast Spectroscopy and Lasers, Electrical Engineering Department, The City College of New York, New York, New York 10031

A new ultrafast optoelectronic switch that utilizes the ferromagnetic semiconductor CdCr$_2$Se$_4$ is demonstrated to have a scope-limited sampled response time of approximately 90 ps.

Picosecond optical switches that use numerous semiconductors such as Si,[1] Cr:GaAs,[2] Fe:InP,[3] and amorphic Si[4] have received much attention. The application of such switches range from material studies to the measurement of the transient response of fast electronic devices. With the use of autocorrelation and cross-correlation techniques,[5] the rapid relaxation of the electronic response due to fast mobility transients, capture, or recombination of optically injected free carriers can be made. With the use of a fast photoconductor as an electrical pulse generator to apply a signal to the device of interest and a second photoconductor acting as a sampling gate, the transient response of the device can be resolved with picosecond resolution.[6] Photoconductive switches with response times ranging from 6 ns to ~10 ps have been reported.[1-4] Variation of responses is attributed to carrier relaxation lifetime, contact effects, and method of biasing the switch.

The ferromagnetic semiconductor CdCr$_2$Se$_4$ belongs to the intensively studied materials of the chromium chalcogenide spinel group. This interest is due to the strong mutual influence of magnetic, optical, and electrical properties, which leads to an anomalous dependence of absorption edge, electrical conductivity, and magnetoresistance on temperature and magnetic field.[7-11] Recently, we reported on the ultrafast photoluminescence recombination time of 3.8 ps for CdCr$_2$Se$_4$ at room temperature.[7] This short carrier recombination time suggests that CdCr$_2$Se$_4$ can be used for an ultrafast on and off optoelectronic switch. As an ultrafast optoelectronic switch that uses picosecond optoelectronic techniques, it is possible to measure the transit mobility and carrier recombination time, giving important information about this relatively obscure material. In this letter we report the performance of a new ultrafast photoconducting switch that uses the ferromagnetic semiconductor CdCr$_2$Se$_4$.

The sample of CdCr$_2$Se$_4$ used in this investigation was grown in a quartz ampule from CdCl$_2$ flux.[8] Single-crystal octahedra 2 mm or more in size were produced by this technique. The lattice parameter was verified by an x-ray powder pattern, and only trace impurities had been revealed by spectrochemical analysis.

Figure 1 shows a schematic diagram of the circuit used to test the optical switch. A sheet of dielectric material, sandwiched between two sheets of copper (copper cladding), was constructed into a microstrip line geometry by etching out two conductive strips from the upper sheet with a 2 mm gap separating them. The CdCr$_2$Se$_4$ sample ($0.5 \times 1 \times 2.0$ mm^3) was attached to the dielectric substrate in the separating gap with an epoxy glue. The connection from the sample to the microstrip line upper electrodes was secured with silver paste. The active region of the photoconductive switch is defined by a 0.5 mm separation (gap) between the electrodes. The dimensions of the microstrip line were such as to produce an approximate 50 Ω characteristic impedance (Z_0). This helps to reduce reflection caused by impedance mismatching. The lower copper sheet of the microstrip line is the ground plate of the device, and a subminiature (SMA) coaxial stripline launcher was attached to each electrode. The SMA-type coaxial stripline launcher connections were secured with silver paste to the electrodes of the switching unit. With a 100 V across the switch, we measured a dark current of 725 mA for a dark resistance of 139 kΩ or a dark resistivity of $\rho_0 = 3.46 \times 10^{3}$ Ω cm.

The excitation consisted of 0.53 μm pulses of approximately 30 ps duration from a frequency-doubled YAG laser. With the use of an EG&G Princeton Applied Research (EG&G) 4420 boxcar averager, 4421 sampled integrator, 4402 signal processor, and a S-4 sampling head, the response of the CdCr$_2$Se$_4$ switch to the 0.53 μm excitation (Fig. 2) displays a rise time (t_r) and fall time (t_f) of approximately 90 ps. The ultrafast switch output signal is limited by the measuring device response time. The jitter of the unit limits its response time to approximately 90 ps. The excitation en-
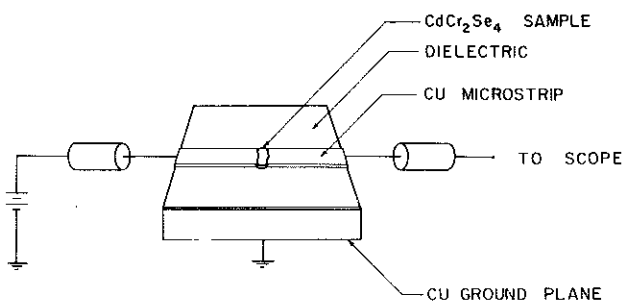

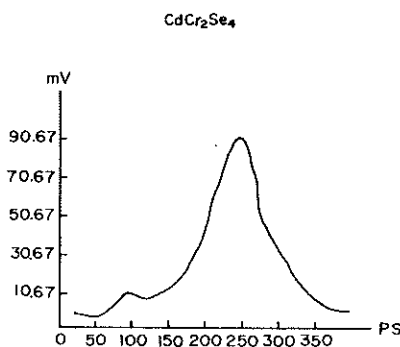FIG. 1. Schematic diagram of the ultrafast CdCr$_2$Se$_4$ switch geometry.

FIG. 2. Sampled response of CdCr$_2$Se$_4$ ultrafast switch to the excitation of wavelength (λ) 0.53 μm ($t_f = t_r \approx 90$ ps).
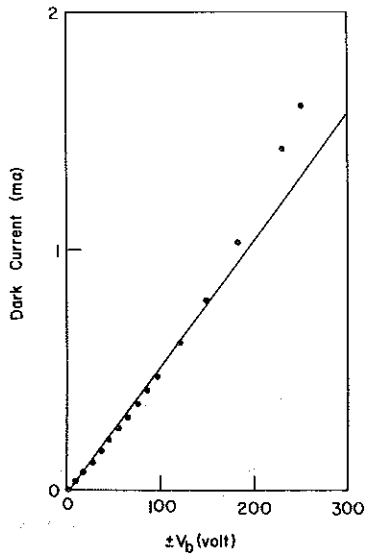
FIG. 3. Dark current as a function of negative and positive voltage.

ergy was 55 μJ (10 Hz repetition rate), the applied bias was 100 V, resulting in a switch responsivity of 5.63×10^{-7} C/J, a quantum efficiency of 1.3×10^{-6}, and a resistance of 35 kΩ ($\rho = 8.8 \times 10^{2}$ Ω cm). For an estimated photoconductive decay time of 4 ps in conjunction with the measured sampling oscilloscope mobility-decay time product of 1.47×10^{-13} cm^2/V, a drift mobility of 0.037 cm^2/V s is calculated. A scope limited real-time response of 350 ps rise and fall time was observed on the Tektronix 7104 oscilloscope. The dark current, bias voltage dependence is linear for a range of -149 to $+149$ V, as shown in Fig. 3. Above 150 V the dark current increases superlinearly. This implies that without excitation the contacts are ohmic up to 149 V. Illustrated in Fig. 4 is the photoconductive response of the ultrafast switch with respect to bias voltage (V_b) under an illumination intensity of 3.1 GW/cm^2 at 0.53 μm. Note that the photoconductive response is linear, which implies that the
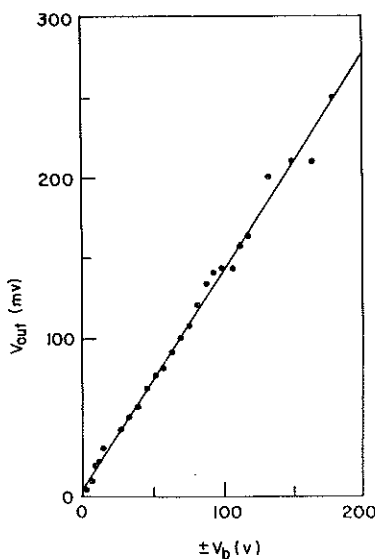

FIG. 4. Bias voltage (V_b) dependence of the photoconductive response (V_{out}) for 0.53 μm at 3.1 GW/cm^2. Note the linear relationship in this case.
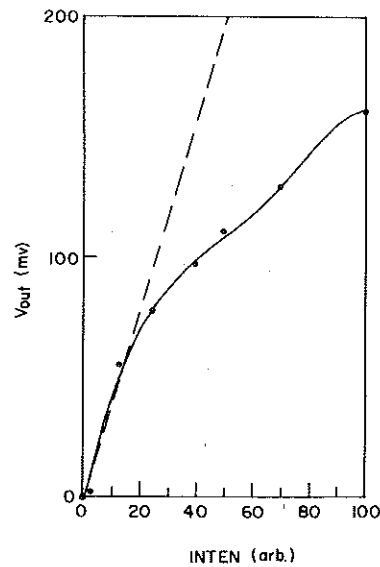

FIG. 5. Photoconductive response as a function of illumination intensity (arb. unit) for 0.53 μm at a maximum illumination intensity of 3.1 GW/cm^2 and a bias voltage of 100 V. Note the sublinear relationship in this case. The broken straight line is shown as a reference.

contacts may be ohmic. However, the sublinear intensity dependence of the photoconductive response of 0.53 μm shown in Fig. 5 indicates that the electrical contacts are nonohmic in character for the carrier densities achieved, and "blocking" contacts do form. One explanation for this behavior is that the contacts could not supply enough carriers to replace those excited by the light pulse; thus the photocurrent would not increase linearly with illumination intensity, but instead would tend to saturate. A space-charge field will be generated near a nonohmic contact, resulting in the collapse of the applied electric field across the semiconductor, which artificially reduces the photoconductive decay time. In addition to a photoconductive decay time that is not representative of electronic transport within the semiconductor, there is usually a fairly strong photovoltaic response. In the case of the CdCr$_2$Se$_4$ switch, there was no photovoltaic response, suggesting (in conjunction with the linear relationship between the photoconductive response and bias voltage) that the contacts are partially nonohmic or at best ohmic. What is meant by the term partially nonohmic is that the metal-semiconductor Schottky barrier width is sufficiently thin to permit tunneling currents to pass through the contacts. The partially blocking contacts may account for the very low quantum efficiency of this switch. The effects of a nonohmic contact to the photoconductive response can be circumvented by applying a pulsed electric field with a temporal duration less than the space charge field build-up time (the dielectric relaxation time). Depending upon the particular semiconductor and the photoexcitation, the dielectric relaxation time can vary from microseconds to femtoseconds. A pulsed bias photoconductive approach has been used to neutralize the effects of dielectric relaxation in low-defect-density amorphous silicon[12] and Fe-doped semi-insulating InP[13] in order to determine the free-carrier relaxation times. In addition to the contact effect explained above, the sublinear response illustrated in Fig. 5 may be due to carrier dy-

namics with deep traps and d levels that are not completely understood at this time.[14]

We have demonstrated the use of the ferromagnetic semiconductor $CdCr_2Se_4$ as an optoelectronic switch with a response time that is less than 90 ps. A more accurate determination of the response time of the $CdCr_2Se_4$ ultrafast switch can be made by using the correlation techniques introduced by Auston et al.[5] From these measurements the carrier mobility and lifetime can be estimated, as well as the effects caused by the contacts (such as dielectric relaxation) separated from the characteristics of the material. Much more work is needed to understand the $CdCr_2Se_4$ sample itself and its uses as an optoelectronic device.

[1] P. R. Smith, D. H. Auston, A. M. Johnson, and W. M. Augustyniak, Appl. Phys. Lett. **38**, 47 (1981).

[2] Chi H. Lee, Appl. Phys. Lett. **30**, 84 (1977).

[3] F. J. Leonberger and P. F. Moulton, Appl. Phys. Lett. **35**, 712 (1979).

[4] D. H. Auston, P. Lavallard, N. Sol, and D. Kaplan, Appl. Phys. Lett. **36**, 66 (1980).

[5] D. H. Auston, A. M. Johnson, P. R. Smith, and J. C. Bean, Appl. Phys. Lett. **37**, 371 (1980).

[6] Donald E. Cooper and Steven C. Moss, IEEE J. Quantum Electron. **QE-22**, 94 (1986).

[7] P. Ho, W. Lam, A. Katz, S. Yao, and R. R. Alfano, IEEE J. Quantum Electron. **QE-22**, 205 (1986).

[8] G. H. Larsen and A. W. Sleight, Phys. Lett. **28A**, 203 (1968).

[9] S. S. Yao, F. Pellegrino, R. R. Alfano, W. J. Miniscalco, and A. Lempicki, Phys. Rev. Lett. **46**, 558 (1981).

[10] W. J. Miniscalco, A. Lempicki, S. S. Yao, R. R. Alfano, N. G. Stoffel, and G. Margaritondo, in *Semiconductors Probed by Ultrafast Laser Spectroscopy II*, edited by R. R. Alfano (Academic, New York, 1984), p. 267.

[11] H. W. Lehmann and M. Robbins, J. Appl. Phys. **37**, 1389 (1966).

[12] A. M. Johnson, D. H. Auston, P. R. Smith, J. C. Bean, J. P. Harbison, and A. C. Adams, Phys. Rev. B **23**, 6816 (1981).

[13] P. M. Downey, D. H. Auston, and P. R. Smith, Appl. Phys. Lett. **42**, 215 (1983).

[14] D. L. Rosen, Q. X. Li, and R. R. Alfano, Phys. Rev. B **31**, 2396 (1985).