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Nanosecond optical quenching of photoconductivity in a bulk GaAs switch

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Persistent photoconductivity in copper-compensated, silicon-doped semi-insulating gallium arsenide with a time constant as large as 30 μs has been excited by sub-band-gap laser radiation of photon energy greater than 1 eV. This photoconductivity has been quenched on a nanosecond time scale by laser radiation of photon energy less than 1 eV. The proven ability to turn the switch conductance on and off on command, and to scale the switch to high power could make this semiconductor material the basis of an optically controlled pulsed-power closing and opening switch.

High-power, bulk, laser-controlled semiconductor switches are of interest for use in lightweight, medium to high power pulse generators. They have so far been mainly used as closing switches for applications requiring fast rise times and low jitter.[1] Closing of the switch is generally achieved by illuminating the switch with band-gap radiation, thus generating electron-hole pairs. The photoconductivity remains high for the duration of the laser pulse, and then decays in the absence of the laser pulse with a time constant determined by bulk recombination of free carriers or by carrier sweep out. In order to achieve short opening times, short electron-hole pair lifetimes are required. However, a short electron-hole pair lifetime represents a large conductivity loss mechanism, which for many applications dictates an unacceptable expenditure of expensive laser photons.

An alternative has been proposed[2] which we have called a bulk optically controlled semiconductor switch (BOSS). The BOSS utilizes the excitation of electrons from deep centers, such as provided by copper in copper-compensated silicon-doped semi-insulating GaAs (Cu:Si:GaAs), to induce photoconductivity. The small cross section for electron trapping into a Cu center allows for long conduction times without continuous laser radiation. Just as important, however, BOSS may be interrupted on command by the application of a second laser pulse of longer wavelength. This laser pulse floods the valence band with free holes, thus inducing a rapid quenching of the photoconductivity over a time scale given by the electron-hole pair lifetime of the material, which can be subnanosecond.

The excitation of long-lived photoconductivity (known as "tail conductivity") at relatively high power has already been demonstrated.[3] The purpose of this letter is to present recent results that demonstrate strong switch opening by rapid laser-stimulated quenching of the tail conductivity.

Low-resistivity, n-type GaAs can be made semi-insulating by the introduction of suitable acceptors into the material through diffusion. One defect is a deep acceptor known as Cu_B, which is located 0.44 eV above the valence band. The addition of the proper density of Cu_B levels into GaAs grown with a shallow donor will result in a highly resistive, compensated crystal.[4]

The crystals used in this investigation were taken from a GaAs wafer grown using the horizontal Bridgman technique.[5] The material was originally doped with silicon to a density of 5×10^{16} cm^{-3}. The crystals were then covered on one side with copper using a vacuum evaporator. The copper layers were approximately 1 μm thick. The samples were placed in a diffusion furnace and annealed in a low-pressure arsenic environment for 2 h. One sample was annealed at 550 °C ($\pm$ 1 °C), while another was annealed at 575 °C ($\pm$ 1 °C). Both samples were then polished and Au-Ge contacts were formed on one side in a planar geometry. Both samples are rectangular in shape with a length and width of about 5 mm. They are both 0.25 mm thick. The contacts are 3 mm wide and form a 2.5 mm gap across the surface of the crystal.

The contacts were annealed at 450 °C for 3 min, after which the dark current-voltage (I-V) characteristics were measured up to a voltage of 100 V. The contacts were observed to be injecting (ohmic). From the I-V characteristics, the resistivity of the crystal annealed at 550 °C was found to be 10^3 Ω cm at 300 K. The resistivity of the crystal annealed at 575 °C was found to be 9×10^4 Ω cm, also at 300 K. Based on estimates of the Fermi level determined from these measurements, coupled with known solid solubility curves for copper in GaAs,[6] we have concluded that the former crystal is undercompensated (n type), while the latter crystal is overcompensated (p type). Further references to the two samples will use these labels. Photoconductivity measurements for the p- and n-type samples are compared in Ref. 7, where the n-type sample is shown to be the better closing switch. This letter concentrates on the opening performance of the p-type sample.

Photoconductivity measurements were performed to test the BOSS concept. Figure 1 illustrates the experimental apparatus. Two different lasers were used to allow two consecutive laser pulses to illuminate the crystal, one for closing the switch, and the other to open it. A Nd:YAG laser ($\lambda = 1.06$ μm, $h\nu = 1.17$ eV) was used to induce the initial conductivity in the crystal (i.e., "turn on" the switch). The laser is Q switched, which results in a Gaussian-shaped temporal response with a full width at half maximum (FWHM) of 26 ns and a peak photon flux of 5×10^{23} cm^{-2} s^{-1} (90 kW/cm^2). The other laser pulse (the "turn-off" pulse) was generated by a tunable laser system formed with a DCR-3 Nd:YAG laser, a PDL pulsed dye laser, and an IR-WEX $LiNbO_3$ mixing crystal, all manufactured by Spectra Physics. The laser has a center wavelength of 1.62 μm, which can be tuned $\pm$ 0.18 μm ($h\nu = 0.77 \pm 0.08$ eV). This laser has a

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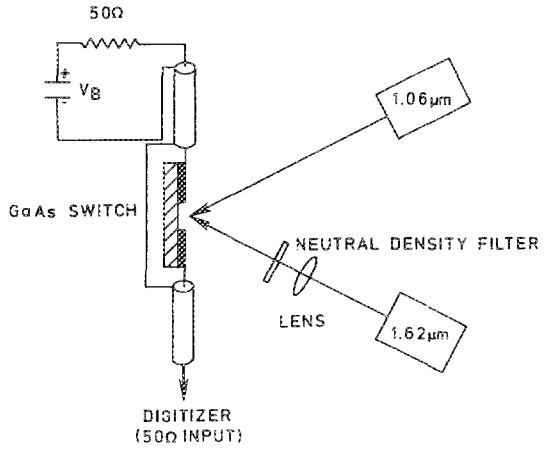

FIG. 1. Diagram illustrating the experimental setup. Note that the crystal was illuminated on the face containing the contacts.

FWHM of 7 ns, and a peak photon flux of 5×10^{25} cm^{-2} s^{-1} (6 MW/cm^2) if the beam is focused onto the active area between the contacts (3mm×3mm).

The bias circuit consists of a capacitor charged to a dc voltage, and connected to the crystal by a long 50 Ω cable (two-way transit time = 275 ns). The initial bias voltage was varied from 40 to ~80V without affecting the photoconductivity of the crystal. In fact, the *p*-type crystal has been demonstrated to exhibit tail conductivity up to a voltage of 3 kV (12 kV/cm).[3] The load is a 50 Ω oscilloscope termination, which acts as a current viewing resistor. These impedances impose a load line of 100 Ω on the switching characteristics of the crystal. The current waveform is digitized by a Tektronix 7912 digitizer.

The complete response of the *p*-type sample to excitation by both laser pulses is illustrated by a typical current waveform shown in Fig. 2. The crystal has first been excited by the 1.06 μm laser pulse, which causes a current overshoot to a peak of more than 0.6 A. The current then decays to a tail of about 0.4 A. After 200 ns, the 1.62 μm laser pulse is incident (photon flux = 5×10^{25} cm^{-2} s^{-1}), which initially creates an increase in current that rapidly gives way to a strong quench. The current decreases below the measurement resolution in under 10 ns.

The response of the current through the *p*-type crystal when the second laser pulse wavelength was increased to 1.8 μm ($h\nu = 0.69$ eV) is shown in Fig. 3. The initial current increase in Fig. 2 associated with the second laser pulse has completely disappeared in Fig. 3, with no apparent reduction in quenching.

The intensity of the second laser pulse was varied from 5×10^{25} to 5×10^{22} cm^{-2} s^{-1} with neutral density filters. Figure 4 shows the intensity dependence of the quenching factor Q, which is defined as

$$Q \equiv \Delta\sigma/\sigma_T,$$

where $\Delta\sigma$ is the difference between the initial tail conductivity and the final quenched conductivity, and σ_T is the initial tail conductivity. The maximum value of Q that could be resolved was about 98%. Figure 4 indicates that Q decreases below 98% at a photon flux of 3×10^{24} cm^{-2} s^{-1}. As the laser intensity decreases, the initial increase in conductivity just prior to the fast quench rapidly diminishes. The initial peak virtually disappears at a photon flux of 5×10^{24} cm^{-2} s^{-1}.

The sample required approximately 1 mJ of 1.06 μm laser energy to induce a tail conductivity of at least 0.5 (Ω cm)$^{-1}$; however, because of the long absorption length for light at wavelengths exceeding the band-gap cutoff, only a fraction of the incident radiation was absorbed (estimated from known cross sections[2] to be slightly more than 1%). At the break point on Fig. 4 (photon flux = 3×10^{24} cm^{-2} s^{-1}), ~0.3 mJ of laser energy at 1.62 μm was expended to quench the conductivity to a final value of about 0.01 (Ω cm)$^{-1}$. The absorption at this wavelength is expected to be stronger, but probably no more than 10%. Therefore, the energy required to turn off the switch is within the same order of magnitude as the energy required to turn it on.

The current response of the Cu:Si:GaAs switch to the two incident laser pulses can be understood by considering the electron gain and loss processes in the semiconductor.

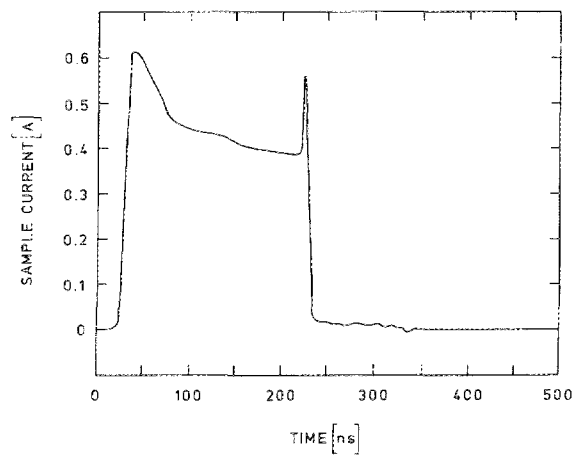

FIG. 2. Measured current flowing through the *p*-type crystal. Sample conductivity is induced initially by the 1.06 μm laser pulse. The sample conductivity is quenched 200 ns later by the 1.62 μm laser pulse. The initial bias voltage is 67 V.

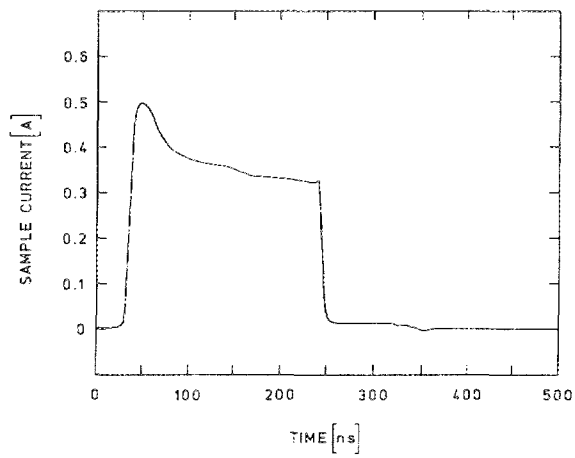

FIG. 3. Measured current flowing through the *p*-type crystal. Sample conductivity is induced initially by the 1.06 μm laser pulse. The sample conductivity is quenched 200 ns later by the 1.8 μm laser pulse. The initial bias voltage is 55 V.

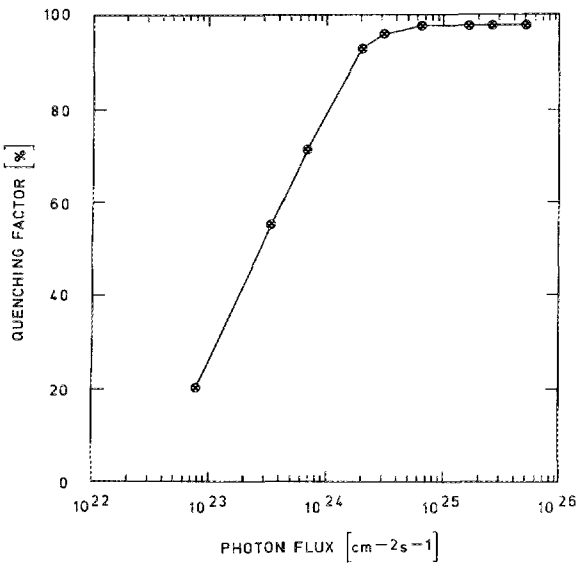

FIG. 4. Quenching factor as a function of the 1.62 μm laser pulse peak intensity. The maximum quenching factor that could be resolved was 98%.

The initial overshoot of the photocurrent (Figs. 2 and 3) is due to electron-hole generation by a two-step process through deep levels. After the first laser pulse is gone a portion of the electrons recombine rapidly with excess holes, either by direct recombination or through fast recombination centers. In addition, electrons may be captured in fast traps, such as EL2. However, the bulk of the conduction electrons decay slowly, because further decay is controlled by the slow capture processes associated with Cu_B.

The second laser pulse applied after about 200 ns quenches the photocurrent. However, for laser wavelengths below 1.75 μm, the photoconductance shows a spike just before the onset of quenching (see Fig. 2). This initial increase in photocurrent is thought to be a two-photon process. Based on published values of the two-photon absorption coefficient[8] we estimate that for our experiment two-photon excitation must be considered when the photon flux exceeds 10^{25} cm^{-2} s^{-1}. A two-photon process will not occur for photon energies less than half the band gap. The fact that the current spike became insignificant when the wavelength was increased to a value above 1.75 μm or the intensity was decreased to a value below 10^{25} cm^{-2} s^{-1} supports the two-photon interpretation of the switch response.

As the second pulse intensity was reduced below the break point on Fig. 4, the fall time of the conductivity did not increase beyond 10 ns. Thus, the electron-hole pair lifetime must be substantially less than the laser pulse width. This fact points, in our opinion, to the presence of recombination centers in the Cu:Si:GaAs crystal, which could have been introduced either during the Cu diffusion or during crystal growth. It is known that recombination center concentrations as small as 10^{15} cm^{-3} in GaAs can result in a subnanosecond electron-hole pair lifetime,[1] which would explain the observed rapid quenching of the photocurrent.

The feasibility of the BOSS concept has been successfully demonstrated with *p*-type Cu:Si:GaAs. Optically controlled closing and opening can be achieved on a nanosecond time scale. According to a rate equation model of the switch, currents on the order of kiloamperes should be controllable with millijoule laser pulses, thus making the material suitable for pulsed power applications. Furthermore, since the concept is not restricted to one particular material, as has been demonstrated with CdS,[9] the shift of the controlling radiation into the visible range should be possible with wider band-gap semiconductors.

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