An Optically Controlled Closing and Opening Semiconductor Switch

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An optically controlled closing and opening semiconductor switch

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A concept for a bulk semiconductor switch is presented, where the conductivity is increased and reduced, respectively, through illumination with light of different wavelengths. The increase in conductivity is accomplished by electron ionization from deep centers and generation of bound holes. The reduction of conductivity is obtained by hole ionization from the excited centers and subsequent recombination of free electrons and holes. The transient behavior of electron and hole density in a high power semiconductor (GaAs:Cu) switch is computed by means of a rate equation model. Changes in conductivity by five orders of magnitude can be obtained.

Energy storage for pulsed power devices commonly implies capacitive storage for which the state of art is relatively well developed. However, in terms of energy density, capacitor banks are inefficient compared to inductive storage systems. Ratios of inductive to capacitive energy density on the order of 100 seem to be obtainable by stressing the technology of coil design. There are two major technical problems in inductive energy storage systems: the limited storage time of magnetic energy due to the energy dissipation in the coil and the development of switches, which can carry high currents.
(tens of kA's) for long times (tens of μs's) and interrupt the current flow in the coil on command in times of microseconds and less. With the advent of new high Tc superconductors the problem of limited storage time for magnetic energy seems to be solvable. The more severe problem—the opening switch design, especially for repetitive operation—is far from being solved. Diffuse discharge switches\(^1\) and bulk semiconductor switches are considered as the most promising candidates for repetitive opening switches so far. In both types of switches the conductivity has to be sustained by external sources: electron beams or lasers.

In order to obtain fast opening times, which for semiconductors means a high electron-hole recombination rate, the sustainment of the conductivity through electron-hole ionization requires a high power source operating for the entire duration of current flow through the switch. The inability to attain both long conduction times and fast opening with reasonable laser power is a fundamental problem of photoconductive semiconductor power switches.\(^2\)\(^-\)\(^4\) Optical control, on the other hand, can provide means to change the conductivity of semiconductors in both directions. Light sources, e.g., lasers, of different wavelengths are then just used to turn the conductivity on and off, not to sustain it. The gain of such a switch compared to conventional photoconductive switches is given as the ratio of sustainment time to the turn on and turn off time, assuming that the power to sustain the conductivity and to induce conductivity transitions is about equal. As will be shown, values of the gain in excess of 10\(^3\) seem to be attainable using a concept which is discussed in the following.

A semiconductor material which has a large electron-hole recombination coefficient is used as base material. The semiconductor is doped with a material which generates deep acceptor levels below the middle of the band gap. The deep centers are assumed to have electron capture cross sections very small compared to hole capture cross sections. The semiconductor is counterdoped with donors in shallow levels in order to fill the deep centers before switching action.

An increase in conductivity—closing of the switch—is obtained through photoionization of trapped electrons from the deep acceptor level into the conduction band by means of a short laser pulse. In addition, electron-hole pairs are generated by two-photon ionization via the vacant deep centers \([\text{Fig. 1(a)}]\). After an initially fast drop of carrier density due to recombination of free electrons and holes, the decay of electrons due to capture into the deep centers is relatively slow \([\text{Fig. 1(b)}]\). Hence, the conductivity remains high for times long compared to the turn-on time. The opening of the switch—reduction of the conductivity—is induced by low-energy photons which ionize the trapped holes into the valence band and stimulate their recombination with the electrons in the conduction band \([\text{Fig. 1(c)}]\).

Such an "inverse" photoconductive effect as described above was reported already in 1957.\(^5\) In CdS, which usually contains traces of copper, quenching of photoconductivity was observed when during irradiation with visible light the crystal was illuminated with infrared radiation. The conductivity quenching was strongest in the wavelength range at about 850 and 1300 nm, respectively. According to the energy level diagram of CdS:Cu (Ref. 10) these wavelengths correspond to transitions from the valence band to deep copper levels and between the copper levels. Experiments on the transient behavior of the conductance of a CdS crystal when irradiated with light of different wavelengths have been performed recently.\(^6\) They have clearly demonstrated the validity of the described switch concept.

Another material which has the required features for the described optically triggered switch is GaAs, doped with copper and counterdoped with silicon.\(^7\) Copper generates deep acceptors in GaAs and Si is a shallow donor impurity. Copper is one of the well-known impurities in III-V compounds. Studies of the direct semiconductor material GaAs show two dominant copper related deep level defects Cu\(_A\) and Cu\(_B\).\(^8\) The Cu\(_B\) level, which is of main interest for our concept, is at 0.44 eV above the valence band. At room temperature the band-gap energy is 1.42 eV for GaAs \((\text{Fig. 2})\).

The photoionization cross sections of holes and electrons for the Cu\(_B\) level were measured by Kullendorf, Janson, and Ledebo.\(^9\) They are shown in Fig. 3 for GaAs. The onset for hole ionization is at 0.4 eV and that for electron ionization is at 1.07 eV, with a peak electron cross section \((\approx 10^{-17} \text{ cm}^2)\) smaller by one order of magnitude than the hole ionization cross section \((\approx 10^{-16} \text{ cm}^2)\). The capture cross sections for holes and electrons for GaAs:Cu\(_B\) are 3×10\(^{-14}\) cm\(^2\) and 8×10\(^{-21}\) cm\(^2\), respectively.\(^10\) Both cross sections are only weakly dependent on temperature.

Numerical calculations of the turn-on and turn-off transients for a GaAs:Cu switch were performed using the rate equations for free electrons \([\text{Eq. (1)}]\), free holes \([\text{Eq. (2)}]\), and bound electrons in the deep centers \([\text{Eq. (3)}]\). In these equations, thermal rates are neglected compared to the optical generation rate and the electron density is small enough so that Auger impact processes are negligible:

![FIG. 2. Energy level diagram of GaAs:Cu:Si at 300 K.](image-url)
The conductivty of the semiconductor is decreased, that means the switch is turned on, by photoionization into the conduction band from the Cu_B level. The photon energy required for this process for GaAs is > 1.1 eV (Fig. 3). For a short laser pulse (10-ns duration) the computed temporal response of the charge carrier density in the conduction band is shown in Fig. 4 in the left segment. It can be seen from this graph that electron and hole densities increase to \(1.7 \times 10^{16}\) cm\(^{-3}\) in about 2-ns time and remains at this value for the duration of the laser pulse.

After turning the laser off at \(t = 10\) ns, the electron density decays due to electron-hole recombination until the hole concentration has reached its steady-state level which is very small compared to its value at \(t = 10\) ns. The remaining electrons, which are excited from the deep level, decay with a time constant determined by the occupancy of the Cu_B centers and the electron capture cross section. Because of the small electron capture cross section, the electron concentration decays only by 5\% of its initial on state value over a period of 10 \(\mu\)s (Fig. 4, middle segment). This slow decay is a desirable feature for the switch since during this state no external energy is required to sustain the conductivity.

The conductivity of the counterdoped semiconductor is increased, that means the switch is turned on, by photoionization into the conduction band from the Cu_B level. The photon energy required for this process for GaAs is > 1.1 eV (Fig. 3). For a short laser pulse (10-ns duration) the computed temporal response of the charge carrier density in the conduction band is shown in Fig. 4 in the left segment. It can be seen from this graph that electron and hole densities increase to \(1.7 \times 10^{16}\) cm\(^{-3}\) in about 2-ns time and remains at this value for the duration of the laser pulse.

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Anisotropic plasma-chemical etching by an electron-beam-generated plasma

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Anisotropic etching of SiO\textsubscript{2} has been achieved with a plasma generated by a broad-area low-energy (150–300 eV) electron beam in a He + CF\textsubscript{4} atmosphere. Etch rates of up to 330 Å/min for SiO\textsubscript{2} and 220 Å/min for Si were obtained. Etching occurred with good uniformity over the entire area exposed to the electron-beam-generated plasma. The fluxes of energetic charged particles to the sample surface are discussed in relation to their possible contribution to the etching process.

We report the first experimental demonstration of anisotropic etching of SiO\textsubscript{2} achieved with the assistance of an electron-beam-generated plasma. It has been previously shown that enhancement of SiO\textsubscript{2}, Si\textsubscript{3}N\textsubscript{4}, and Si etching is obtained through the use of energetic electrons.\textsuperscript{1,2} In comparison with ion beams of the same energy, beam electrons induce less crystalline damage.\textsuperscript{1} Consequently, low-energy electron-beam-assisted etching has been proposed as source of low-damage etching.

Coburn and Winters demonstrated that Si\textsubscript{3}N\textsubscript{4} and SiO\textsubscript{2}

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