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An Optically Controlled Closing and Opening Semiconductor Switch

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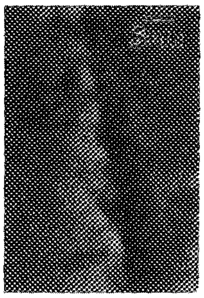

FIG. 4. Transmission electron micrograph of SIPOS/silicon interface (1.575×10^6 magnification). Epitaxial dendrites attached to the silicon (dark) are visible (the orientation is most easily viewed by holding the page at a shallow angle).

appears dark and the crystal planes are evident). There is a high density of epitaxial dendrites of silicon which are seen to protrude from the silicon into the SIPOS layer. One often sees twinning in these dendrites and they are easily distinguished from the randomly oriented crystallites which are always present in annealed SIPOS films. Films which were deposited on improperly cleaned silicon showed a lower dendrite density or, in some cases where a visible oxide film was present, none at all. These structures corroborate the conclusion from the above analysis that there is a source of enhanced field emission in our capacitors.

In summary we have seen clear evidence of a new low field current component in the *I-V* and *C-V* traces of SIPOS capacitors. We suggest that our data show the transition between a field emission regime, which is mediated by silicon dendrites at the SIPOS/silicon interface, and the bulk conduction regime, which has been described by a symmetrical Schottky barrier model.[1,3]

Since power electronic devices rely upon SIPOS, as a passivant and as a means of shielding surface devices from the electric fields concomitant with high-voltage metal overruns, factors which affect its properties when interfaced with silicon are of concern. The amount of native oxide at the interface has been thought[4,5] for some time to have an effect on the way SIPOS influences electrical potentials near the surface. We have shown that the cleaning procedure used before SIPOS deposition has a marked effect on conduction through the interface. Carim *et al.*[11] have recently shown (with transmission electron and scanning tunneling microscopy) that cleaning with hydrofluoric acid, as opposed to a peroxide clean, reduces the area of coverage and the thickness of silicon's native oxide. Cleaning with hydrofluoric acid and minimizing the delay before SIPOS deposition is proving to have a positive effect on breakdown voltage values for certain lateral power devices (these results will be discussed in another paper).

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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.[1] With the advent of new high T_c 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[2] 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.[3-8] 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 [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 [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 [Fig. 1(c)].

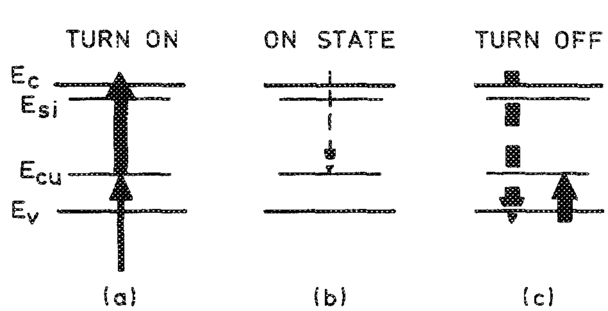

FIG. 1. Optical ionization processes (solid lines) and recombination processes (dashed lines) during the different stages of the switch.

Such an "inverse" photoconductive effect as described above was reported already in 1957.[9] 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.[11] 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.[12] 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.[13] 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 (Fig. 2).

The photoionization cross sections of holes and electrons for the Cu_B level were measured by Kullendorf, Jansson, and Ledebo.[13] 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 ($\approx 10^{-17}$ cm^2) smaller by one order of magnitude than the hole ionization cross section ($\approx 10^{-16}$ 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.[14] 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 [Eq. (1)], free holes [Eq. (2)], and bound electrons in the deep centers [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:

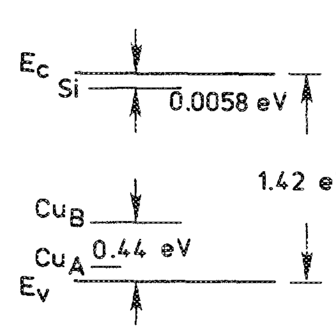

FIG. 2. Energy level diagram of GaAs:Cu:Si at 300 K.

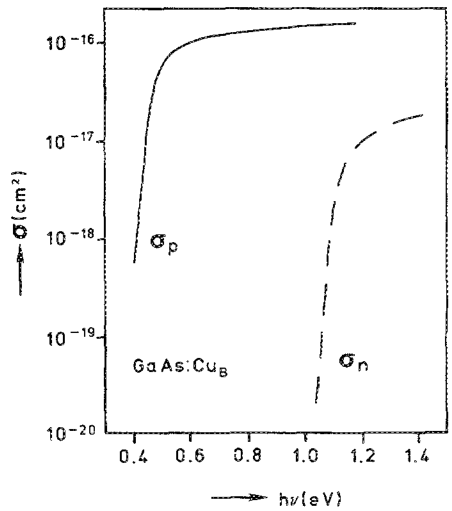

FIG. 3. Photoionization cross sections of holes (σ_p) and electrons (σ_n) for GaAs:Cu_B at 60 K [from N. Kullendorf, L. Jansson, and L. A. Ledebo, J. Appl. Phys. **54**, 3203 (1983)].

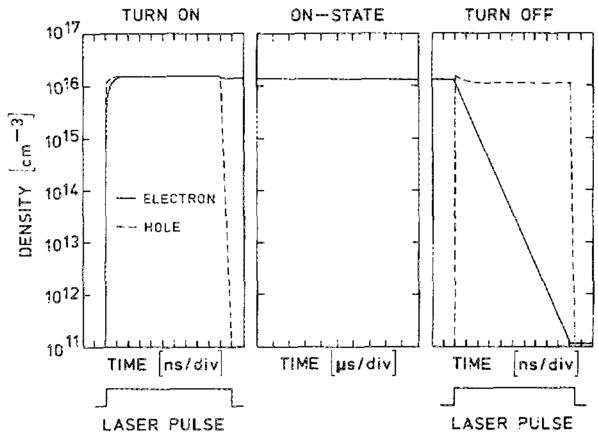

FIG. 4. Computed temporal variation of charge carrier densities during the different stages of a GaAs:Cu switch.

$$\frac{dn}{dt} = \sigma_n^0 \phi n_T - c_n n(N_{TT} - n_T) - k_d np, \tag{1}$$

$$\frac{dp}{dt} = \sigma_p^0 \phi (N_{TT} - n_T) - c_p p\, n_T - k_d n\, p, \tag{2}$$

$$\frac{dn_T}{dt} = c_n n(N_{TT} - n_T) + \sigma_p^0 \phi (N_{TT} - n_T) - \sigma_n^0 \phi n_T - c_p p n_T, \tag{3}$$

n: free electron density,

p: free hole density,

n_T: density of electrons in deep centers,

N_{TT}: density of deep centers (10^{17} cm^{-3}),

c_n: electron capture parameter (8.3×10^{-14} cm^3 s^{-1}),

c_p: hole capture parameter (2.8×10^{-7} cm^3 s^{-1}),

σ_n^0: electron ionization cross section (10^{-17} cm^2),

σ_p^0: hole ionization cross section (10^{-16} cm^2),

k_d: rate coefficient for free electron/free hole recombination (10^{-7} cm^3 s^{-1}),

ϕ: photon flux (5×10^{25} cm^{-2} s^{-1}).

The above equations were solved numerically using a fourth-order Runge–Kutta technique. The numbers in the parentheses are the data used for the numerical simulation. For the shallow donor density N_D a value of 5×10^{16} cm^{-3} was used. The capture parameters and photoionization cross sections shown above are taken from the papers by Lang and Logan[14] and Kullendorf and co-workers,[13] respectively. The value for the direct recombination coefficient k_d is of the order of 10^{-10} cm^3 s^{-1} for pure GaAs.[15] In semi-insulating GaAs, however, the electron-hole recombination is determined by recombination via deep centers. For the calculation it was therefore assumed that the influence of the various deep centers on the electron-hole recombination in semi-insulating GaAs can be described by one parameter k_d. The value of k_d was chosen to be 10^{-7} cm^3 s^{-1} in accordance with the experimentally obtained conductivity decay time which is of the order of 10 ns. The photon flux for turn-on and turn-off was assumed to be equal. The results of the calculation are shown in Fig. 4.

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 $\geqslant 1.1$ 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 1.7×10^{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 μs (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 semiconductor is decreased, that means the switch is turned off, by hole photoionization from the Cu_B level. The photon energy required for this process is $0.4 \text{ eV} \leqslant h\nu \leqslant 1.05$ eV for GaAs:Cu_B (Fig. 3). For the numerical simulation a 10-ns laser pulse with a photon energy of 0.5 eV was assumed. This photon energy is not high enough to ionize electrons but only to ionize holes. The hole ionization opens a channel for band-to-band recombination, a fast process which is determined by the electron-hole recombination cross section and by the density of generated holes and available electrons. The electron concentration decays rapidly by five orders of magnitude within a few nanoseconds (Fig. 4, right segment). The decay of free holes after turn-off is even faster, due to the very large hole capture cross section of the Cu_B state. The hole concentration drops by five orders of magnitude in less than 0.5 ns. As a result, the conductivity of the GaAs:Cu material is reduced from $\approx 20\ \Omega^{-1}$ cm^{-1} to about $2\times10^{-4}\ \Omega^{-1}$ cm^{-1}.

The opening effect, that means the reduction of conductivity by stimulated electron-hole recombination is strongly dependent on the value of the direct recombination rate coefficient. Rate equation calculations with $k_d \approx 10^{-10}$ cm^3 s^{-1}, characteristic for pure GaAs (Ref. 15) showed that with the same laser power and duration the conductivity drop is four orders of magnitude less than for $k_d = 10^{-7}$ cm^3 s^{-1}. Generally, the faster the electron-hole pair recombination, the less laser energy is required to open the semiconductor switch.

In all these calculations it was assumed that during the switching process transitions between impurity levels can be neglected. Second, it was assumed that nonlinear processes do not contribute to the population of energy levels. For high-power switches triggered by high-power lasers, multiphoton process impose limitations on the maximum obtainable switch current density. Another limitation is given by impurity interactions and cluster formations at high-impurity concentrations.

The outstanding features of the described switch are that it can be turned on and turned off on command without jitter on a nanosecond and faster timescale and that it does not require external energy to sustain the conductivity in the on state. The application of this type of switch is not limited to pulsed power systems, but can be extended to any system where bistable elements with fast temporal response and optical control are required.

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

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Anisotropic etching of SiO_2 has been achieved with a plasma generated by a broad-area low-energy (150–300 eV) electron beam in a He + CF_4 atmosphere. Etch rates of up to 330 Å/min for SiO_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_2 achieved with the assistance of an electron-beam-generated plasma. It has been previously shown that enhancement of SiO_2, Si_3N_4, and Si etching is obtained through the use of energetic electrons.[1–3] In comparison with ion beams of the same energy, beam electrons induce less crystalline damage.[1] Consequently, low-energy electron-beam-assisted etching has been proposed as source of low-damage etching.

Coburn and Winters demonstrated that Si_3N_4 and SiO_2

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