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Influence of copper doping on the performance of optically controlled GaAs switches

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The influence of the copper concentration in silicon-doped gallium arsenide on the photoionization and photoquenching of charge carriers was studied both experimentally and theoretically. The studies indicate that the compensation ratio (N_{Cu}/N_{Si}) is an important parameter for the GaAs:Si:Cu switch systems with regard to the turn-on and turn-off performance. The optimum copper concentration for the use of GaAs:Si:Cu as an optically controlled closing and opening switch is determined.

Recently Schoenbach *et al.* introduced a novel concept for a bulk optically controlled semiconductor switch (BOSS), which can be turned on and turned off by two lasers with different wavelengths.[1] The feasibility of the BOSS concept has been demonstrated with CdS:Cu (Ref. 2) and with GaAs:Si:Cu (Refs. 3 and 4). In this communication we investigated silicon-doped gallium arsenide with diffused copper (GaAs:Si:Cu). Si introduces a shallow donor level [$E_{Si} = E_c - 0.0058$ eV (Ref. 5)] in GaAs and Cu introduces two primary deep acceptor levels ($E_{Cu_A} = E_v + 0.14$ eV and $E_{Cu_B} = E_v + 0.44$ eV).[6] At thermal equilibrium, most of the electrons ionized from the shallow donor are trapped at the deep acceptors. Hence the initial electron occupation of the deep acceptor levels is determined by the density of the shallow donor. The switch concept is based on photoionization of the deep acceptor (turn-on) and then the subsequent photoquenching of the previously generated free carriers (turnoff). Photoquenching of the BOSS is obtained by creating free holes through the photoexcitation of electrons from the valence band to the Cu_B level. The free electrons at the conduction band can then recombine with the free holes at the valence band by direct band-to-band recombination and by recombination through recombination centers. Since GaAs is a direct semiconductor material, relatively fast turn-off can be achieved through direct band-to-band recombination. The turn-off transient characteristics can be further improved by introducing fast recombination centers such as Cr into the GaAs material, which can lead to subnanosecond turn-off times.[7]

Two GaAs samples were prepared.[4] One was an *n*-type sample where the shallow donor, Si, was undercompensated by the deep acceptor Cu ($N_{Si} = 5\times10^{16}$ cm^{-3}, $N_{Cu} \simeq 4.5\times10^{16}$ cm^{-3}). The other was *p* type, where the shallow donor Si was overcompensated by the deep acceptor Cu ($N_{Si} = 5\times10^{16}$ cm^{-3}, $N_{Cu} \simeq 10^{17}$ cm^{-3}). The base material, GaAs material doped with Si at a concentration of 5×10^{16} cm^{-3}, has been characterized by deep-level transient spectroscopy (DLTS).[8] Two defect levels located at 0.83 and 0.41 eV below the conduction band were detected and identified as the *EL* 2 level ($N_{EL2} \simeq 7\times10^{15}$ cm^{-3}) and the *EL* 5 ($N_{EL5} \simeq 2\times10^{15}$ cm^{-3}) level, respectively (Fig. 1).[9] These defects are known as native electron traps in GaAs and affect the on-state performance of the switch by capturing free electrons at the traps. A possible fast recombination center introduced during Cu diffusion is chromium (Cr) located at about the middle of the band gap. The parameters for the fast recombination center were estimated from the photoconductivity decay of the test samples. The estimated value of the density of the recombination center which is denoted as RC in Fig. 1 is $N_{RC} = 3\times10^{14}$ cm^{-3}. The electron-capture cross section (σ_n) and the hole-capture cross section (σ_p) are estimated as $\sigma_n = 10^{-13}$ cm^2 and $\sigma_p = 10^{-13}$ cm^2, respectively.[7] The energy-level diagram of GaAs:Si:Cu material is shown in Fig. 1. The concentration of Cu_A is about 20% of Cu_B where $N_{Cu} = N_{Cu_B}$.[6]

The temporal variation of the photoconductivity of the two switch samples is shown in Fig. 2. A Nd:YAG laser was used to turn the switches on [wavelength $\lambda = 1.06\,\mu$m, peak photon flux $\Phi_1 \simeq 10^{24}$ cm^{-2} s^{-1}, full width half maximum (FWHM) = 26 ns]. A tunable infrared laser system was used to turn the switches off (wavelength $\lambda = 1.8\,\mu$m, peak photon flux $\Phi_2 = 10^{25}$ cm^{-2} s^{-1} and FWHM = 7 ns). The conductances and conductivity of the two switch samples were calculated from photocurrent measurements and normalized to eliminate the geometrical differences between the two samples. Higher on-state conductivity was obtained in the *n*-type sample than the *p*-type sample.

The experimental results clearly show the existence of long-lived "tail" conductivity (on-state), which is attributed to the electron contribution from the deep acceptor (Cu_B). It can be seen from the figure that the *p*-type sample (overcompensated) provided better turn-off performance

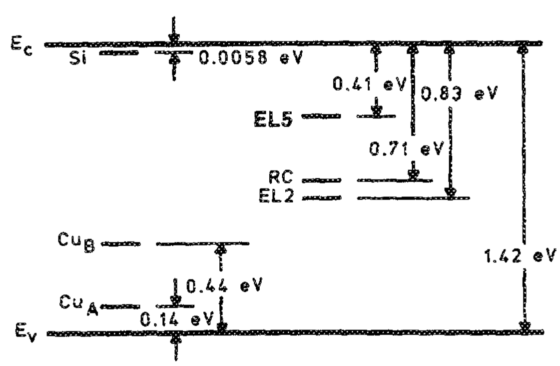

FIG. 1. Energy-level diagram of the BOSS (GaAs:Si:Cu) system used for the simulation.

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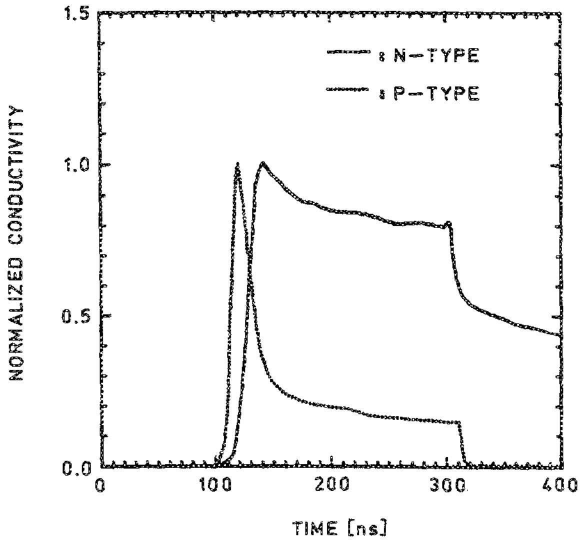

FIG. 2. Experimental results of the photo-conductivity measurement in the two samples.

compared with the n-type (undercompensated) sample and that the turn-off transient time of the switches are on the order of nanoseconds. This fast decay cannot be explained by direct radiative recombination; it indicates the existence of fast recombination centers in the samples.

Based on the experimental data and deep-level parameters from various papers,[10] the switch systems have been numerically simulated. The model uses rate equations for the densities of free electrons, free holes, and bound electrons at all trap levels.[1,10] The rate equations include the Auger recombination process and two-photon ionization process. In the previous model,[1] recombination through fast recombination centers was included in the direct recombination coefficient k_d. Here, recombination through fast recombination centers is considered separately from direct band-to-band recombination. Assumptions made in the model are that the temporal profile of the laser pulses are Gaussian, and that electron transitions between defect levels are negligible.

Figure 3 shows the result obtained from the numerical simulation for the two switch samples. Two important aspects of the BOSS are clearly visible: the existence of the long tail conductivity (on-state) and fast photoquenching (turn-off). It is also seen from the figure that n-type material provides better on-state conductivity while p-type material gives stronger photoquenching during the turn-off phase of the switch. The decay time of the photoquenching is on the order of nanoseconds. The simulated curve has a slower decay rate during the on-state (after the turn-on pulse) than the experimental curve. This discrepancy is believed to be due to surface recombination, which was not considered in our model.

Two important parameters determining the on-state conductivity and the photoquenching are the photoionization rate of electrons k_{ei} and the photoionization rate of holes k_{hi} at the Cu_B level, which are

$$k_{ei} = \sigma_n^0 \Phi_1 n_{Cu_B}, \qquad (1)$$

$$k_{hi} = \sigma_p^0 \Phi_2 (N_{Cu_B} - n_{Cu_B}), \qquad (2)$$

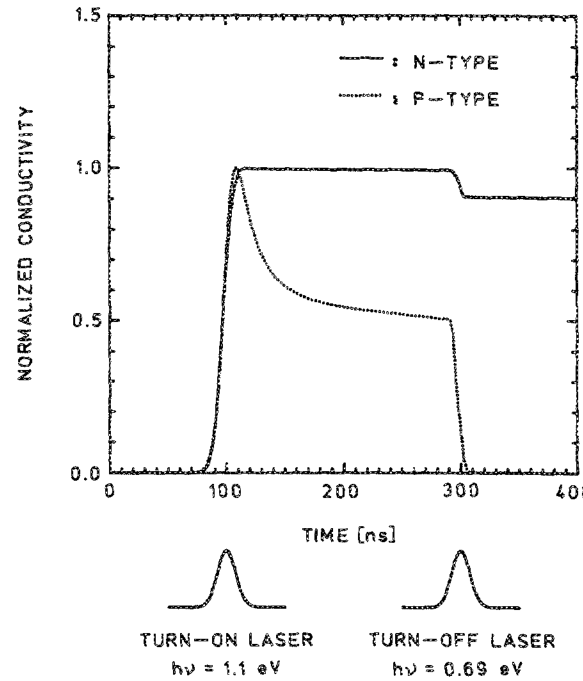

FIG. 3. Simulated photoconductivity of the two samples during the switching operation.

where Φ_1 is the turn-on photon flux, Φ_2 the turn-off photon flux, σ_n^0 the electron photo-ionization cross section, σ_p^0 the hole photoionization cross section, n_{Cu_B} the density of Cu_B centers occupied by electrons, and N_{Cu_B} the total density of Cu_B centers. In the BOSS, the electron ionization from the Cu_B level to the conduction band is the process that determines the on-state conductivity of the switch, because electron ionization at the laser wavelength of 1.06 μm is possible only through the Cu_B level. The n-type material has a higher electron concentration n_{Cu_B}, and hence it has a higher electron ionization rate k_{ei} than the p-type material. Consequently higher on-state conductivity is obtained in the n-type sample compared to the p-type sample. In the p-type sample, on the other hand, the hole ionization rate is higher than for the n-type material because of a higher hole concentration $(N_{Cu_B} - n_{Cu_B})$. Hence the p-type sample provides better photoquenching. These facts are clearly demonstrated in the experimental as well as in the calculated results.

Further numerical simulations were performed to provide a basic guideline for optimizing the Cu concentration with respect to the photoquenching efficiency. The calculated on-state (before turn-off laser irradiation) and turn-off (after turn-off laser irradiation) conductivity as a function of the compensation ratio, N_{Cu}/N_{Si} are plotted in Fig. 4. The results show that the higher the Cu density the lower is the on-state conductivity. On the other hand, the higher the Cu density the higher is the quenching ratio (the ratio of turn-on to turn-off conductivity). A small change in the Cu concentration affects the turn-off characteristics of the switch drastically.

The choice of the Cu concentration in the GaAs switch material depends on the application of the switch itself. The undercompensated or fully compensated material (n type, $N_{Cu}/N_{Si} \leqslant 1$) is suitable for closing switches with a high on-

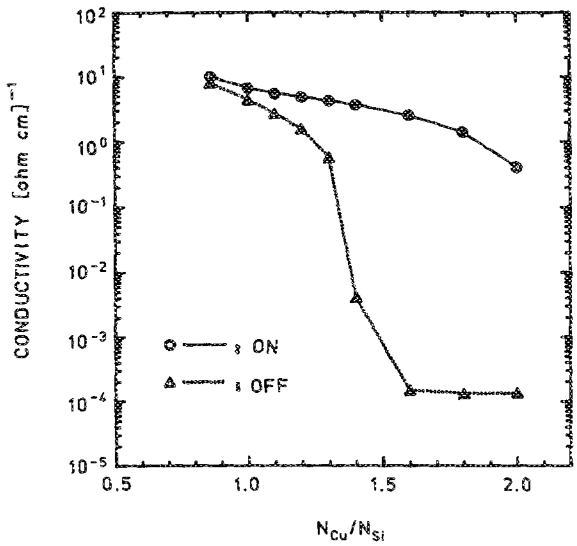

FIG. 4. On-state and turn-off conductivity as a function of the compensation ratio (N_{Cu}/N_{Si}). Parameters used in the calculation are turn-on laser photon flux (Φ_1) of 2×10^{24} cm^{-2} s^{-1}, turn-off laser photon flux (Φ_2) of 10^{25} cm^{-2} s^{-1}, and a shallow donor density (N_{Si}) of 5×10^{16} cm^{-3}.

state conductivity at a given turn-on photon flux. The overcompensated material (p type, $N_{Cu}/N_{Si} > 1$), on the other hand, is better suited for opening switches because of more efficient quenching. For the use of the system as both a closing and opening switch, there exists an optimum Cu concentration because the quenching ratio is proportional to Cu concentration while the on-state conductivity is inversely proportional to it. For example, if strong photoquenching (conductivity change greater than 4 orders of magnitude) and relatively high on-state conductivity is desired, the optimum Cu density would be 8×10^{16} cm^{-3} ($N_{Cu}/N_{Si} \simeq 1.6$).

Both experimentally observed and calculated photoconductivities have been presented, showing the dependence of the BOSS performance on the Cu concentration. This dependence allows one to generate GaAs:Si:Cu switches for a wide variety of applications by changing the concentration of the impurity in the GaAs material over relatively small ranges. These variations can easily be controlled by changing the Cu diffusion process in GaAs:Si.

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The theoretical basis of application of fractal to fracture physics

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A theoretical basis to support the application of the fractal approach in fracture physics is put forward. According to the theory, if Griffith's criterion is approved, the fractal approach can be used.

Fractal and fractal geometry was first proposed by Mandelbrot in 1975.[1] He used this geometry to describe irregular or fragmental objects. In recent years, fractal geometry has been used in more and more fields of science; for example, fracture physics, materials science, etc. Through the analysis of specimen surface[2] or failure surface,[3,4] the fractal dimension D_f and the relationship between D_f and residual life, fracture toughness K_{ic} were obtained. But there is no theoretical basis to support the application of fractal approach in fracture physics. This paper is going to solve this problem. The problem has been studied by Dong.[5] The conclusion is that the fractal approach is in conflict with Griffith's criterion.

His calculation is as follows: The criterion of crack growth is

$$G_{IC} = 2r + r_p , \qquad (1)$$

where r is the unit surface energy, and r_p is unit surface plastic energy. For small range yield, we can suppose:

$$r_p \gg 2r. \qquad (2)$$

Thus, $G_{IC} = r_p$.