Numerical Analysis for the Optically Controlled Bistable Semiconductor Switches

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Summary

Cu compensated Si doped GaAs (GaAs : Si : Cu) has been chosen as the switch material. Simulation studies are performed on several GaAS switch systems, composed of different densities of Cu, to investigate the influence of deep traps in the switch systems. The computed results demonstrates important aspect of the switch, the existence of stable high conductivity (on-state) and fast optical quenching (turn-off). Some important parameters such as high conductivity saturation and optimum Cu density for the switch are determined.

Introduction

The idea of optically controlled bistable semiconductor switch using deep impurity levels has been developed by Schoenbach (Schoenbach et al., 1988) and the feasibility of the switch concept has been demonstrated in the CdS : Cu system (Germer et al., 1988) and the GaAs : Si : Cu system (Ko et al., 1990 and Mazzola et al., 1989).

The switch concept is based on photoionization of electrons from the deep level (such as Cu_B in GaAs) and optical quenching of the electrons (Schoenbach et al 1988). The increase of the conductivity (turn-on) is obtained by two step electron ionization from the Cu_B level. The wave length is chosen such that the photon energy ($h\nu$) is less than the band gap energy (E_g) of GaAs. Hence the direct electron ionization from the valence band to the conduction band is prodhibited. At the end of the turn-on laser pulse, the electrons contributed from the deep levels remain in the conduction band and the switch stays on for times much longer than the duration of the laser pulse. The decrease of conductivity (turn-off) is achieved by ionizing

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holes from Cu_B level. The wavelength of this turn-off laser pulse is chosen such that the photon energy ($h\nu$) is less than the energy of (E_c-E_{CuB}), but greater than the energy(E_{CuB}-E_v). This allows for the free electrons in the conduction band to recombine with free holes at the valence band. Hence, the switch returns to the original high resistivity state resulting in a fast opening action. Since GaAs is a direct semiconductor material, fast turn-off of the switch is obtained. The turn-off transient characteristics can be further improved by introducing a fast recombination center such as Cr into the GaAs material. With such a recombination center, subnanosecond turn-off time can be achieved (Weiner et al., 1984).

Switch Material

The switch material studied for the present work was Si doped GaAs with diffused Cu (GaAs : Si : Cu). The Si in GaAs introduces a shallow donor level (E_{si}=E_c-0.0058 eV) (Sze et al., 1968) and the Cu introduces two primary deep acceptor levels (E_{CuA}=E_v+0.14eV and E_{CuB}=E_v+0.44eV) (Lang et al., 1975). At thermal equilibrium, most of the electrons donated from the shallow donor are trapped at the deep acceptors. Hence the initial electron occupation of the deep acceptor levels is controlled by the density of the shallow donor.

The base material, Si doped GaAs material, has been characterized by the Deep Level Transient Spectroscopy (DLTS) technique (Lang, 1974). Figure 1 shows a typical DLTS spectrum obtained for the GaAs : Si : Cu switch sample. Two defect levels located at 0.83 eV and 0.41 eV from the conduction band were detected (figure 1) and identified as the EL2 level and the EL5 level respectively (Ko, 1989). These defects are known as native defects in the GaAs material and affect the on-state of the switch by capturing the free electons at the traps.

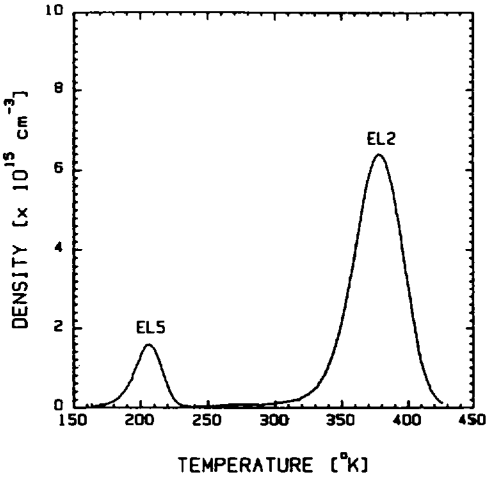

Fig. 1. A typical DLTS spectrum measured on the Si doped GaAs material.

Previous photo-conductivity measurements on the Si doped GaAs with diffused Cu indicated the existence of a fast recombination center, Cr (Mazzola et al., 1989). The estimated density of the recombination center is 3×10^{14}cm^{-3}. The electron capture cross section and hole capture cross section for the

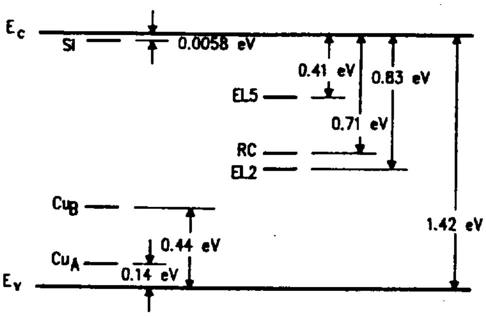

Fig. 2. Energy level diagram of the switch (GaAs : Si : Cu) system used for the simulation.

Cr estimated are $\sigma_n = 10^{-13}cm^{-2}$ and $\sigma_p = 10^{-13}cm^{-2}$ respectively (Weiner and Yu, 1984). Figure 2 shows the energy level diagram of the switch material used for the simulation studies in this paper. RC in the figure denotes the recombination center.

Switch Modeling

Switch simulation has been performed by using a set of rate equations for free electrons, free holes and the bound electrons at traps as shown below (Ko, 1989) :

$$\frac{\partial n}{\partial t} = \frac{\beta h\nu\Phi^2}{2} + \Sigma e_{ni} n_{Ti} - k_d np - \Sigma c_{ni} n (N_{Ti} - n_{Ti}) - k_a n^2 p \qquad (1)$$

$$\frac{\partial p}{\partial t} = \frac{\beta h\nu\Phi^2}{2} + \Sigma e_{ni}\, n_{Ti} - k_d np - \Sigma c_{ni} p n_{Ti} + k_a n^2 p \qquad (2)$$

$$\frac{\partial n_{Ti}}{\partial t} = (C_{ni} n + e_{pi}) N_{Ti} - (C_{ni} n + c_{pi} p + e_{ni} + e_{pi}) n_{Ti} \qquad (3)$$

where n, p : free electron, free hole density,

N_T : total trap density,

n_T : trap density occupied by electrons,

$h\nu$: photon energy,

k_d : direct band-to-band recombination coefficient,

k_a : Auger recombination coefficient,

$c_{n,p}$: electron, hole capture parameter,

$e_{n,p}$: electron, hole emission rate,

Φ : photon flux.

Here the subscript i is used to denote the "i" th trap. The rate equations were numerically solved by using a fifth order Runge-Kutta technique with adaptive grid control (Press et al., 1986). The parameters used in the simulation are listed in Table 1.

TABLE 1 Typical values used in the computation

parameters		value	references
σ_n	(CuB)	8×10^{-21} cm^2	(Lang, 1975)
σ_p	(CuB)	3×10^{-14} cm^2	(Lang, 1975)
σ_{no}	(CuB)	10^{-17} cm^2	(Kullendorf, 1983)
σ_{po}	(CuB)	10^{-16} cm^2	(Kullendorf, 1983)
σ_n	(EL2)	4×10^{-15} cm^2	(Mitonneau, 1979)
σ_p	(EL2)	2×10^{-18} cm^2	(mitonneau, 1979)
σ_{no}	(EL2)	8×10^{-17} cm^2	(Martin, 1980)
σ_{po}	(EL2)	3×10^{-17} cm^2	(Martin, 1980)
σ_n	(EL5)	5×10^{-15} cm^2	(Mitonneau, 1979)
σ_p	(EL5)	2×10^{-18} cm^2	〔*〕
σ_{no}	(EL5)	10^{-17} cm^2	〔*〕
σ_{po}	(EL5)	10^{-17} cm^2	〔*〕
σ_n	(CuA)	8×10^{-21} cm^1	〔*〕
σ_p	(CuA)	3×10^{-14} cm^2	〔*〕
σ_{no}	(CuA)	10^{-17} cm^2	〔*〕
σ_{po}	(CuA)	10^{-16} cm^2	〔*〕
β		26 cm/GW	(Bogges, 1985)
κ_a		10^{-33} cm^{-6} s^{-1}	(Takeshima, 1972)
κ_d		7×10^{-10} cm^3 s^{-1}	(Demokan, 1983)

* The values are not known and have been assumed as reasonable values.

Results and Discussion

Two laser pulses at different wavelengths are used for the photo-ionization and photo-quenching. One laser pulse with photon energy of 1.1 eV (FWHM=26 ns) is used to increase the conductivity (turn-on) and the second laser with photon energy of 0.7 eV (FWHM=7 ns) is used to decrease the conductivity (turn-off). The temporal shape of the laser pulse is assumed to be Gausssian.

To investigate the effect of Cu compensated on the switch performance, two switch systems are considered-one n-type where Si is under compensated by Cu ($N_{si}=5\times10^{16}cm^{-3}$ and $N_{cu}=4.5\times10^{16}cm^{-3}$) and the other p-type where Si is overcompensated by Cu ($N_{si}=5\times10^{16}cm^{-3}$ and $N_{cu}=10^{17}cm^{-3}$).

The computed temporal variation of the conductivity (turn-on) for the n-type switch with photon flux as a parameter is shown in figure 3. The peak of the turn-on laser pulse is located at t=50 ns in the figure. The long stable high conductivity (on-state) after the laser is off is clearly demonstrated. Saturation of the on-state conductivity with the increase in incident photon flux can also be seen in the figure. Increasing the intensity beyond saturation value results in a fast rise time and a higher initial (peak) conductivity, but the on-state conductivity is not increased. The turn-on characteristics for the two switch systems are summarized in figure 4. The on-state conductivity here is the conductivity, at t=200 ns. It can be seen in the figure that the on-state conductivity reaches a saturation value at a photon flux of about $10^{25}cm^{-2}s^{-1}$ (1.8MW/cm^2) for both systems. This saturation is mainly because of the fact that the free electrons for the on-state conductivity are contributed from the Cu_B level. The density of free electrons for the on-state conductivity is, therefore, limited by the density of Cu_B level occupied by electrons at thermal equilibrium.

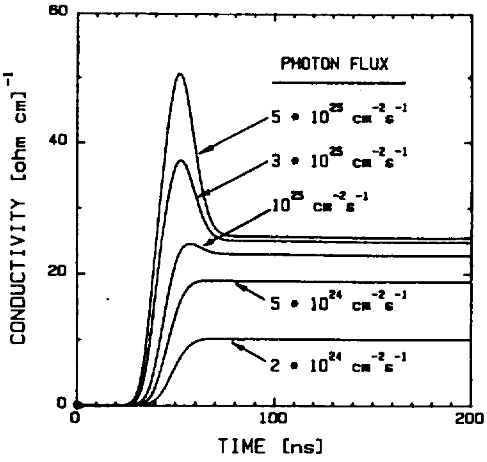

Fig. 3. Computed temporal variation of the conductivity with incident photon flux as the parameter during turn-on for the n-type switch.

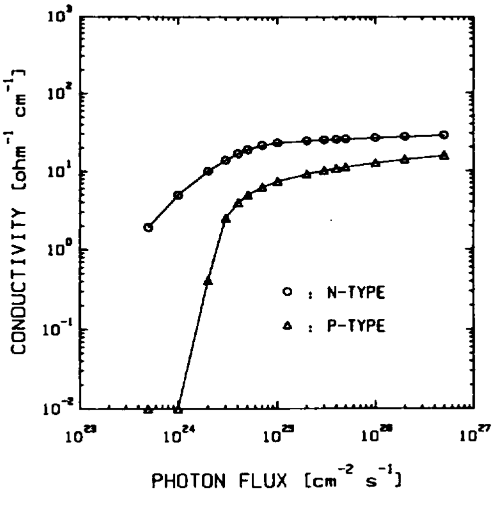

Fig. 4. Variation of the on-state conductivity as a function of photon flux.

The photo-ionization efficiency for turn-on of the switch dereases because of the on-state saturation. The efficiecny as a fucntion of the incident photon flux is plotted in figure 5. The efficiency here is defined as the number of on-state free electrons ionized by one photon. An efficiency less than one indicates that more than one photon is required to ionize one free electron for the on-state conductivity. The low efficiency at high photon flux, as seen, is mainly due to the on-state saturation. It is clearely shown that the n-type switch gives better turn-on efficiency than the p-type switch at a given photon flux.

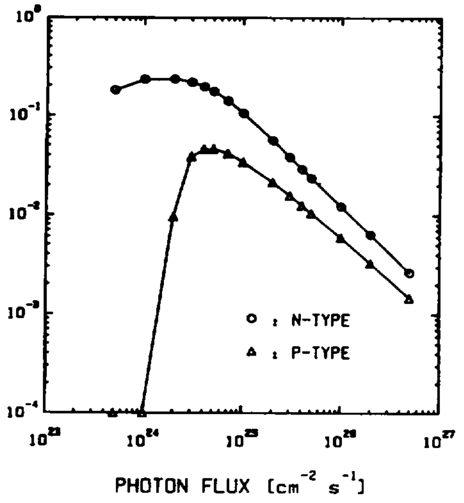

Fig. 5. Photo-ionization efficiency as a function of the incident photon flux.

Further numerical simulations were performed to provide a basic guideline on the Cu doping concentration for better photo quenching efficiency. Figure 6 shows the turn-off conductivity as a function of the Cu density and the turn-off photon flux. Here, the shallow donor density of 5×10^{16} cm^{-3} and turn-on photon flux of 2×10^{24} cm^{-2}s^{-1} are used. The result demonstrates that the higher the Cu density, the higher is the quenching efficiency.

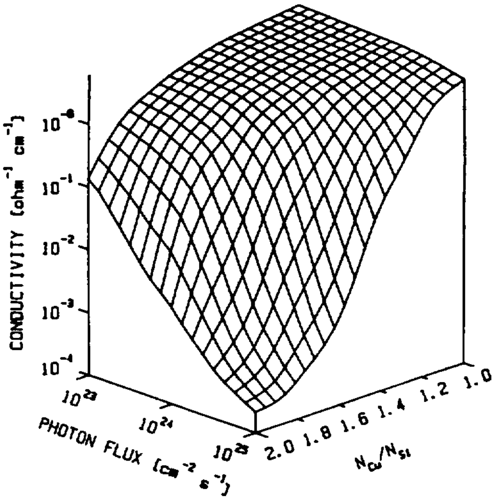

Fig. 6. Simulated turn-off conductivity of the switch as a function of incident photon flux and the N_{cu}/N_{si} ratio.

The choice of the Cu concentration in the GaAs switch material depends, however, on the application of the switch itself. The full and under compensated (n-type, $N_{cu}/N_{si}\leq1$) material is more suitable for closing switches, since one can obtain high on-state conductivity at a given turn-on photon flux. The over compensated (p-type, $N_{cu}/N_{si}>1$) material on the other hand is better for opening switches because of a higher quenching efficiency. Since the quenching efficiency is proportional to Cu concentration while the on-state conductivity is inversely proportional to it, there exists an optimum Cu concentration for the use of the system as both closing and opening switches. For example the optimum Cu density is $N_{Cu}=8\times10^{16}$ cm^{-3} ($N_{Cu}/N_{Si}=1.6$) for a given photon flux of 10^{25} cm^{-2}s^{-1}. The temporal variation of photo-conductivity for a system with optimum Cu density (solid line) is shown in figure 7 and compared with the n-type (dashed line) and the p-type (dotted line). It is seen from the figure that for the weekley p-type material ($N_{Cu}=8\times10^{16}cm^{3}$), strong optical quenching (greater than four order of magnitude change in conductivity) is obtained. The result clearly demonstrate that small change in Cu density affects a drastic change in on-state conductivity as well as turn-off conductivity. The decay time of the optical quenching is on the order of nanoseconds.

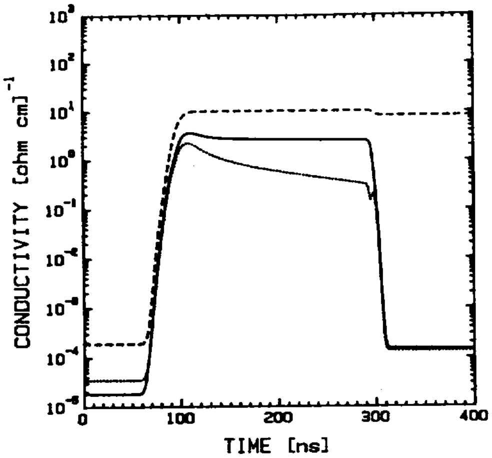

Fig. 7. Computed temporal variation of photoconductivity during the switching operation for the three cases : n-type (dashed line), the optimum Cu density (solid line) and p-type (dotted line).

Conclusions

Simulation studies are performed on an optically controlled GaAs : Si : Cu switch using a set of rate equations. The influence of Cu on the performance of the switch is clearly demonstrated in the computed results. Several other important parameters such as on-state saturation, maximum ionization efficiency and optimum Cu density as a function of photon flux have been determined for optically controlled bistable switch. The modeling result indicates that over compansation with Cu ($N_{Cu}/N_{Si}>1$) is required for bistable operation and there exist an optimum Cu compensation ($N_{Cu}/N_{Si}\approx1.6$). The rate equation model provides better understanding of the switch and a basic guideline for better switch design.

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國文抄錄

광 제어 쌍안정 반도체 스위치에 대한 수치적인 해석

Si이 도핑된 후 Cu로 보상된 GaAs가 스위치 물질로 선택되었다. Deep 불순물들이 스위치 시스템에 미치는 영향을 조사하기 위해 여러가지 농도로 도핑된 GaAs 스위치 시스템에 대해서 콤퓨터 씨뮬레이션이 수행되었다. 콤퓨터에 의해 계산된 결과는 스위치에 대한 다음의 두가지 중요한 양상을 보여주고 있다. 즉 안정되고 높은 전도의 상태(도통상태)와 빠른 빛에 의한 캐리어의 소거(차단상태)를 보여준다. 또한 스위치에 대한 중요한 파라메터인 최적의 Cu 농도와 높은 전도상태의 포화 조건 등이 결정되었다.