Infrared Photoconductivity via Deep Copper Acceptors in Silicon-Doped, Copper-Compensated Gallium Arsenide Photoconductive Switches

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Abstract—**Silicon-doped, copper-compensated, semi-insulating gallium arsenide of various doping parameters has been studied with respect to infrared photoconductivity. This material is used as a photoconductive switch known as the Bistable Optically controlled Semiconductor Switch (BOSS). This device is a candidate for use in high-power, frequency agile pulsed power applications. One limitation has been the relatively low conductivity of the device during the "on-state." Typically, silicon-doped gallium arsenide is converted to semi-insulating gallium arsenide by the thermal diffusion of copper into the GaAs:Si. We have shown that variation of the diffusion parameters can improve the on-state conductivity by the enhancement of the concentration of a copper center known as Cu_B. The conductivity of the device 150 ns after irradiation from a 20-ns FWHM laser pulse (λ = 1.1 μm) is recorded for various incident energies. This on-state conductivity saturates at a value that is predicted by the densities of the copper levels and the mobility. Also, the samples were irradiated with a 140-ps FWHM laser pulse (λ = 2 μm) in order to excite holes from the copper levels into the valence band which demonstrates the nature of the hole recapture into the various copper acceptors.**

I. Introduction

PHOTOACTIVE devices, such as metal–semiconductor–metal and p-i-n photodetectors are well known for their subnanosecond switching performance [1]. Devices using the p-i-n configuration are of particular interest to the device community because they represent one of the simplest device structures available for studying current-transport phenomena, especially at microwave frequencies [2], [3]. A device of more recent interest is the photoconductive switch [4], which is essentially a light-activated p-i-n diode scaled to many times the typical size. The photoconductive switch is viewed as a possible alternative to high-power tubes in pulsed-power applications. The presumed advantages of photoconductive switches are their nanosecond to subnanosecond performance, high-repetition-rate operation, lack of jitter, and the notion of scalability. Scalability arises from the properties of the semiconductor bulk characteristics of the device. Thus a millivolt microscopic device or a kilovolt macroscopic device should be equally possible by holding the electric field and current density constant while adjusting the device dimensions. For example, the Bistable Optically controlled Semiconductor Switch (BOSS) is a photoconductive switch in which the conductivity in the "i" region formed by copper-doped semi-insulating GaAs can be modulated with laser pulses of two different wavelengths [5], [6].

The BOSS technology relies on the fabrication of semi-insulating gallium arsenide using silicon and copper dopants. Silicon-doped gallium arsenide can be converted into semi-insulating gallium arsenide by the introduction of deep copper acceptors by thermal diffusion [7], [8]. This device can be activated by the application of a short (nanosecond) infrared laser pulse (λ = 1.1 μm), and the photoconductivity persists for microseconds [9]. The persistent photoconductivity gives rise to an important switching parameter for the BOSS device called the on-state conductivity. It has been shown that the on-state conductivity can be reduced by at least five orders of magnitude over a few nanoseconds by the application of a second laser pulse (λ = 2 μm) [10]. This means that the BOSS switch is a true opening switch because the voltage is completely re-established across the device after the rising edge of the 2-μm laser pulse. The maximum on-state conductivity of the switch measured in the past has been 1 $(\Omega \cdot \text{cm})^{-1}$, which leads to switch resistances of around 20 Ω. For high current operation (1 kA), the BOSS device would have excessive power dissipation in the switch resulting in switch failure. Also, the current through a gallium-arsenide-based device is ultimately limited by drift velocity saturation, which is an electric-field-dependent effect. This implies that current saturation will occur for on-state voltages of only a few kilovolts, and therefore the maximum current that can be delivered to a load can only be improved by an improvement of the on-state conductivity.

The on-state conductivity is closely related to the density of the copper level that is being excited by the laser pulse. Copper forms several deep acceptors in GaAs:Si,

Manuscript received October 22, 1992; revised January 26, 1993. The review of this paper was arranged by Associate Editor J. J. Coleman.

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IEEE Log Number 9208279.

and the three most often reported levels are called Cu_A, Cu_B, and Cu_C as shown in Fig. 1 [7], [11]. The Cu_B level is used in the BOSS switching cycle due to the long lifetime of electrons excited from Cu_B into the conduction band. Also, the position of Cu_B in the band diagram allows for the use of two laser wavelengths which are a factor of two apart to activate and quench the conductivity. Most of the important features of Cu_B such as capture cross sections, optical ionization cross sections, and activation energy are given by Lang [12], and Kullendorf [13], both using the Deep Level Transient Spectroscopy (DLTS) method.

The BOSS concept can be modeled temporally using (1)–(3)

$$\frac{\partial n}{\partial t} = G_n - U_n \tag{1}$$

$$\frac{\partial p}{\partial t} = G_p - U_p \tag{2}$$

$$\frac{\partial r_i}{\partial t} = \dot{r}_{vi} + \dot{r}_{ci} \tag{3}$$

where n and p are the free electron and hole densities, respectively, G and U represent generation and recombination terms, r_i is the occupation number defined as the ratio of trapped charge to total trap density (n_{Ti}/N_{Ti}) and $\dot{r}_{ci}$, $\dot{r}_{vi}$ represent trapping and thermal-release rates of electrons or holes [14]. The recombination is expressed as

$$U_n = k_d np + \sum_{i=1}^{m} c_{n_i} n(N_{T_i} - n_{T_i}) \tag{4}$$

$$U_p = k_d np + \sum_{i=1}^{m} c_{p_i} p n_{T_i} \tag{5}$$

where k_d is the direct recombination coefficient ($cm^3 \cdot s^{-1}$), N_T is the density of the deep level (cm^{-3}), n_T is the density of electrons at the deep level (cm^{-3}), c_n and c_p are the capture parameters ($cm^3 \cdot s^{-1}$), and the subscript i represents the various levels to be considered. The electrical conductivity can be written in terms of the free electron and hole concentrations (n, p)

$$\sigma = \mu_n nq + \mu_p pq \tag{6}$$

where μ is the mobility, and q is the electronic charge. Two special cases will be investigated here. The first will involve the excitation of electrons from Cu_B into the conduction band using the turn-on laser pulse ($\lambda = 1.1$ μm), and the second case is that of hole excitation from the various copper levels into the valence band using the turn-off laser ($\lambda = 2$ μm).

For the case of irradiation with the 1.1-μm laser pulse, the saturation of the on-state conductivity is defined by assuming that the Cu_B level is approximately full of electrons initially, and that all of these electrons are excited into the conduction band by the laser pulse. These assumptions are justified by measurements of the Fermi level (obtained through Hall and Van der Pauw measurements) which has been located between the Cu_B level and the middle of the bandgap, and the fact that saturation of the photocurrent generated from the photoexcitation of Cu_B must occur when the Cu_B level becomes filled with holes. A final consideration is that of hole excitation from Cu_B into the valance band which occurs during excitation by the 1.1-μm laser pulse. The cross section for electron photoexcitation (10^{-17} cm^2) is an order of magnitude smaller than that for holes (10^{-16} cm^2) [13], however, the combination of fast hole capture and slow electron capture processes at Cu_B causes the electron concentration at Cu_B to become predominantly depleted [5] after application of the 20-ns FWHM (1.1-μm) laser pulse. Direct (band-to-band) recombination is then the loss mechanism. Therefore, the saturation on-state conductivity (σ_{ss}) may be expressed as

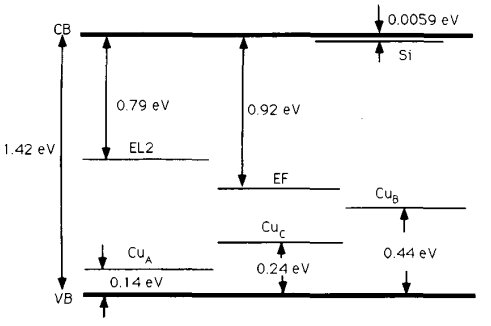

Fig. 1. Energy band diagram for GaAs:Si:Cu with the deep donor EL2 and the Fermi-level EF.

$$\sigma_{ss} = \mu_n N_{Cu_B} q \tag{7}$$

where N_{Cu_B} is the density of the Cu_B level. It should be noted that the photon energy of the turn-on laser (1.1 eV) is sufficient to excite electrons from Cu_B into the conduction band while excluding transitions from Cu_A and Cu_C into the conduction band.

The second case is that of hole excitation from the copper levels into the valence band using the 2-μm laser pulse (140-ps FWHM). This experiment is significant because, for the BOSS device operation, the electron current generated by the 1.1-μm laser pulse is quenched by direct recombination with holes generated by the 2-μm laser pulse. Therefore, the hole capture cannot be faster than the direct recombination time, or there will be a negligible quenching effect. Also, investigating the hole capture processes gives insight into the deep-level structure in our switch material. The hole capture time constant may be measured during the time after the peak laser intensity. For this case, the electron current can be neglected ((1) and (4)) because the 2-μm wavelength excludes transitions from any copper acceptor into the conduction band. We will consider the case where there are three copper acceptors (Cu_A, Cu_B, and Cu_C). The conductivity of the switch after the laser pulse has ended involves a genera-

tion term (G_p) in which emission must be considered

$$G_p = \sum_{i=1}^{m} e_{p_i} N_{T_i}(1 - r_i) \tag{8}$$

where m represents the number of deep levels to be considered, and e_{pi} is the emission parameters (s^{-1}), and r_i is the occupation number ($r_i = n_{Ti}/N_{Ti}$). Since the electron current has been neglected, then the direct recombination term in (5) can also be neglected. Rewriting (2) to include (5) and (8), and linearizing ($r_i p \approx p$) gives

$$\begin{aligned}\frac{dp}{dt} = {} & p(-c_{p_1} N_{\mathrm{Cu_A}} - c_{p_2} N_{\mathrm{Cu_B}} - c_{p_3} N_{\mathrm{Cu_C}}) \\ & + (1 - r_1) e_{p_1} N_{\mathrm{Cu_A}} + (1 - r_2) e_{p_2} N_{\mathrm{Cu_B}} \\ & + (1 - r_3) e_{p_3} N_{\mathrm{Cu_C}}\end{aligned} \tag{9}$$

where $r_1 = n_{\mathrm{Cu_A}}/N_{\mathrm{Cu_A}}$, $r_2 = n_{\mathrm{Cu_B}}/N_{\mathrm{Cu_B}}$, and $r_3 = n_{\mathrm{Cu_C}}/N_{\mathrm{Cu_C}}$ are the occupation numbers for the deep acceptor levels. The occupation numbers may be written as

$$\frac{dr_1}{dt} = e_{p_1}(1 - r_1) - c_{p_1} p \tag{10}$$

$$\frac{dr_2}{dt} = e_{p_2}(1 - r_2) - c_{p_2} p \tag{11}$$

$$\frac{dr_3}{dt} = e_{p_3}(1 - r_3) - c_{p_3} p. \tag{12}$$

The eigenvalues for the homogeneous system of linearized equations, obtained by making the variable substitution $(1 - r_i) \equiv x_i$ in (9)–(12), are given by the roots of

$$\lambda(\lambda^3 + A\lambda^2 + B\lambda + C) = 0 \tag{13}$$

where A, B, and C are rather lengthy functions of the deep-level densities, and capture and emission parameters. Equation (13) implies a solution for the free hole density that takes the form of three exponentials and a dc term.

Equations (7) and (9)–(13) represent the special cases that will be addressed in the experiments to follow. One important feature of these equations is that the silicon density (or free electron density) is a known constant for each experiment. Also, the laser pulses used in the experiments isolate the specific effects that we wish to study, which are electron excitation from Cu_B into the conduction band and hole excitation from the copper centers into the valence band. It is understood that for the latter case there may be significant hole excitation from levels other than Cu_B due to the fact that the partition ($\gamma = (N_{\mathrm{Cu_A}} + N_{\mathrm{Cu_C}})/N_{\mathrm{Cu_B}}$) may be much larger than one, and the photon energy of the 2-μm laser pulse is sufficient to involve transitions from Cu_A, Cu_B, or Cu_C to the valence band. If the partition is dominated by Cu_B, however, then any holes excited from Cu_A can be neglected because the Fermi–Dirac statistics dictate that there should be a negligible number of holes at Cu_A in comparison to Cu_B.

II. Experiments

The first experiment involves the measurement of the saturation on-state conductivity (σ_{ss}) which is defined in (7). Samples were prepared by diffusing copper into GaAs:Si through an annealing process. This process has shown that compensation is achieved when the density of diffused copper is approximately equal to or slightly greater than the density of ionized silicon. Therefore, the temperature at which compensation occurs depends on the density of free electrons prior to the copper diffusion, and this means that the total copper density (N_{Cu}) is known for each silicon density when the diffusion temperature is such that compensation is observed [8]. The samples are typically placed in an evacuated quartz tube along with solid sources of copper and arsenic. The reason for using an arsenic source is to control the diffusion of arsenic into and out of the sample during diffusion. Arsenic vacancies and complexes are believed to be associated with many deep levels in GaAs including copper. Three samples have been prepared which had initial free electron densities of 1×10^{16}, 2×10^{16}, and 5×10^{16} cm^{-3}. Duplicates of these samples were also prepared with the exception that they were exposed to larger arsenic partial pressures during the diffusion process. The temperatures at which compensation occurred for each of these samples were 550, 580, and 659°C, respectively. These temperatures correspond to copper solubility data given by others which show that the copper concentrations approximately equal the silicon concentrations at these temperatures ($N_{Cu} = N_{Si}$) [8].

Each sample was prepared with coplanar, Au:Ge, ohmic contacts (2.5-mm spacing, 3-mm width). The devices are prepared with copper leads attached by silver epoxy and they are mounted into a 50-Ω microstrip line which was connected to the diagnostics. The approximate size of each sample is 5 mm × 5 mm × 0.6 mm. The load resistor used in the first experiment was 1 Ω which ensures that the sample voltage can be easily extracted from the measured voltage. The voltage across the charging capacitor (2.6 μF) was measured, and the current was measured by recording the voltage across the 1-Ω load resistor. The samples were biased to 30 Vdc. The laser was incident on the sample from the back face (opposite the contacts) in order to uniformly illuminate the entire volume beneath and between the contact metallizations. The laser used in this experiment was Nd:YAG with a Gaussian 20-ns FWHM temporal shape. The maximum output energy was measured using a volume absorbing power meter to be approximately 12 mJ. The energy absorbed in the sample was calculated based on a reflection coefficient of 0.32, and taking multiple internal passes through the thin samples into account. The purpose of this experiment was to change the laser energy incident on the sample by inserting a series of neutral density filters into the beam path and plotting the resulting photoconductivity of the sample for the various laser energies. The expected result is that the photoconductivity will saturate when the Cu_B level is depleted of electrons as described by (7). Fig. 2

shows the results of the experiments and it is apparent that the density of the copper level has been enhanced by using material with initial silicon densities increased from 1×10^{16} to 5×10^{16} cm^{-3}. The dependence of the saturated on-state conductivity on the arsenic pressure in the ampoule during diffusion is also shown in this figure, and it appears that the lowest arsenic pressure results in the higher values of σ_{ss}. In fact, using measured values of the mobility and the knowledge of the total copper density and a constant partition, σ_{ss} can be predicted using (7) to be 1 $(\Omega \cdot \text{cm})^{-1}$ for $N_{Cu} = N_{Si} = 1 \times 10^{16}$ cm^{-3}, and 4 $(\Omega \cdot \text{cm})^{-1}$ for $N_{Si} = 5 \times 10^{16}$ cm^{-3}. These values closely match the experimental data for a partition (γ) of about 7.

The next experiment involves the investigation of (9)–(13). The purpose is to directly measure the hole trapping time after a 2-μm laser pulse excites holes from Cu_A, Cu_B, and Cu_C into the valence band for samples of different values of N_{Si}. Due to the location of the Fermi level, the copper levels are nearly filled with electrons, however, there are small densities of holes available for excitation by the laser pulse. For strong illumination, the use of n-type contacts is justified for p-type majority-carrier conduction because the time constant associated with the displacement current (due to the n-p anode junction) is much longer than the time window of the experiment. As shown in (9)–(12), there is a dependence of the hole trapping time constant on the density of the deep traps in the material. The laser pulse has sufficient energy to elevate electrons from the valence band to the copper centers, but insufficient energy to elevate electrons from the copper centers into the conduction band. This means that the observed conductivity decay should involve only hole capture back into the copper centers. Linearization of the equations is therefore reasonable because these centers were nearly full of electrons initially.

Each of the samples tested in the previous section were next irradiated with a 2-μm, 140-ps FWHM laser pulse. The incident energy of the laser was varied from about 100 μJ up to about 4 mJ due to the change in absorption depth which results from using material with different copper concentrations. By adjusting the laser energy such that the photoconductivity was the same for each sample, the energy absorbed was held approximately constant for each sample. The decay of the photoconductivity was recorded after the peak intensity of the Gaussian laser pulse was reached. The measured decay times for the generated photoconductivity in two samples are shown in Fig. 3. Curve fits (solid lines in Fig. 3) involving three exponentials and a constant term fit the data accurately for the solid circles, but not quite as well for the triangles possibly because one of the time constants extends too far beyond our rate window. The time constants associated with the triangles in Fig. 3 are 5.4, 1.5, and 0.92 ns. The solid circles in Fig. 3 have time constants of 0.88, 0.35, and 0.32 ns. Due to their similarity, the latter two time constants do not appear to represent well-separated deep levels. However, these time constants are convolved with

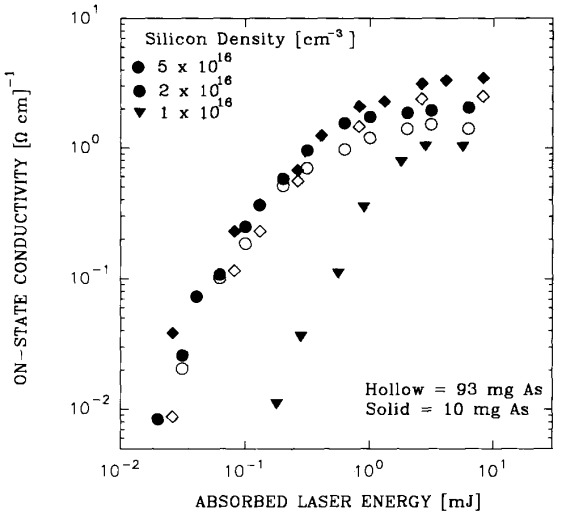

Fig. 2. Saturation of the photoconductivity in GaAs:Si:Cu for various doping densities and processing conditions.

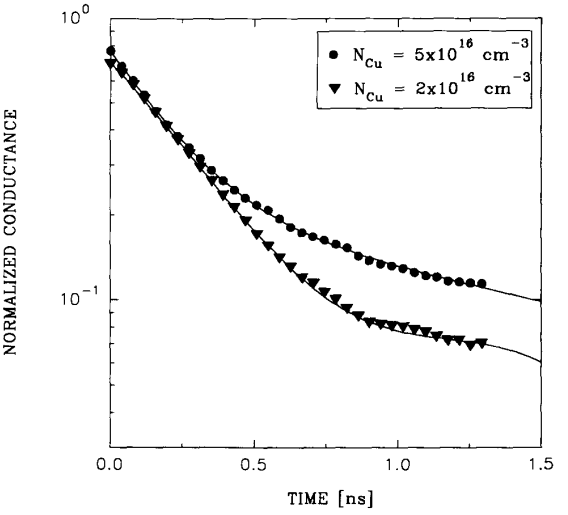

Fig. 3. Decay of the photoconductivity for GaAs:Si:Cu after irradiation from a 140-ps FWHM infrared (λ = 2 μm) laser source.

the fall time of the laser and may be separated more than they appear to be. The important conclusion is that the data in Fig. 3 demonstrate that the decay times increase with decreasing copper density. Also, the curve fits reveal that (13) may be a valid form to describe the time constants involved. From our experiments, which involved one rate window, it appears that the samples with the highest doping densities have decay transients which involve more than two deep acceptor levels. This is not conclusive, however, due to the small separation in the time constants which appear in our rate window.

III. Discussion

Two important parameters in the operation of the bulk photoconductive switch known as BOSS have been explored: 1) On-state conductivity, and 2) response to 2-μm

radiation. The saturated on-state conductivity (σ_{ss}) is crucial to the operation of this device because it determines the power dissipation in the device, which ultimately limits the power output of the system. This on-state conductivity was shown to be dependent on the doping densities of copper and silicon. For higher doping densities (5×10^{16} cm^{-3}), the on-state conductivity saturated at approximately 4 $(\Omega \cdot \text{cm})^{-1}$, whereas the lower density material (1×10^{16} cm^{-3}) saturated at about 1 $(\Omega \cdot \text{cm})^{-1}$. It was also shown that the arsenic partial pressure during the copper diffusion steps influences the saturated on-state conductivity. The experiments show that the lower arsenic content in the ampoule resulted in the highest values of σ_{ss}. The reason for this may be the dependence of the Cu_B level on arsenic vacancies and/or interstitials. These results are significant because they show that the device can be improved by enhancing the deep levels in the switch material through semiconductor processing techniques.

The second set of experiments focussed on the excitation of the switch with a fast (140-ps), 2-μm laser pulse. The goal was to observe the recapture of holes excited from the copper centers back into their equilibrium state. A simple rate equation model involving three deep acceptors demonstrated that capture and emission processes are important, and that the time constants change according to the copper concentration. The solution to (9)–(12) involves three exponentials and a constant, which are all dependent on the capture/emission parameters, and the densities of the deep levels. The experiments demonstrated that the time constants for samples of different copper densities were consistent with those expected from the equations. For the higher density material ($N_{Cu} = 5 \times 10^{16}$ cm^{-3}), three exponentials may be within our rate window, but for the lower density material ($N_{Cu} = 2 \times 10^{16}$ cm^{-3}) it appears that at least one of the exponentials is somewhat longer and extends beyond our rate window. The important result is that the time constants increase with decreasing doping densities. It is understood that the faster time constants are convolved with the laser fall time which means that the actual time constants may be smaller than they appear. Our results imply that the BOSS opening effect seems to be feasible on a subnanosecond time scale as long as the recombination between electrons in the conduction band and holes in the valence band occurs on a subnanosecond time scale.

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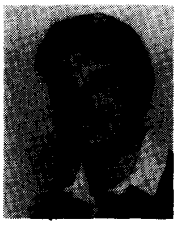

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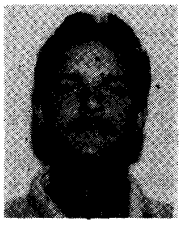

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