A HIGH CURRENT DENSITY THYRISTOR-LIKE GALLIUM PHOSPHIDE BASED OPTOELECTRONIC SWITCH

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Abstract

A thyristor- like optoelectronic switch with high current density is investigated. The switch is based on the optoelectronic bistability exhibited by certain GaP light emitting diode-type structures at 77K. The bistability is based on the negative differential resistance that occurs during the forward biased current-voltage (I-V) characteristic. A model has been developed to explain the observed s-shape I-V characteristic and describe the dependence of the I-V characteristic on the geometry of the device, doping species and concentrations. The switching time depends on the intensity of optical gating signal, bias voltage and doping concentrations. The device has high current density capability (~10^4 A/cm^2), can be triggered optically, and its geometry and doping concentrations can be readily controlled and varied. The model has a general applicability to III-V based pulsed power switches.

Introduction

A thyristor-like optoelectronic switch is investigated for high current applications. The switch is based on the optoelectronic bistable behavior exhibited by gallium phosphide light emitting diodes [1],[2]. Recent results include the development of a model that explains the observed thyristor like I-V characteristic in terms of an electron lifetime increase due to the saturation of electron traps and a thermal effect due to current increase. The switching mechanism is similar to that present in diodes with asymmetric doping and long base, compared to the diffusion length of the minority carriers, [3]-[6]. Experimentally observed results indicate the strong dependence of the switching time delay on the bias voltage and the optical trigger signal intensity.

Experimental results-Modeling

The GaP diodes studied, showed bistable characteristics in the current, the optical output intensity and the optical output peak wavelength. The ON state current was observed to reach as high as 700 mA with a forward voltage drop of approximately 8 V.
Switching to the ON state is achieved with an optical trigger signal (a 500-nm, 100 μJ, 5-ns dye laser pulse). The negative resistance region in the I-V characteristic extends over several hundred mA for a device with area ~500 μm^2. The shift in electroluminescence frequency from the low current state (with λ~568nm) to the high current state (λ~547nm) is tentatively attributed to the nitrogen related radiative recombination centers which become active at different current states [7].
Based on the model described below, initially the bulk region of the diode is of high resistivity (>10^3 Ohm.cm). The p-side bulk is partially compensated by deep oxygen donors which are positively charged at thermal equilibrium at 77K. At low voltages the current consists of minority diffusion components on either side of the junction. Radiative recombination occurs inside the space charge region of the junction mainly through nitrogen and donor-acceptor routes. The electron diffusion length is short (less than 1μm).

At a certain current value the electron injection rate into the p-side bulk region becomes higher than the recombination rate. When this occurs radiative recombination will extend deeper into the p-side bulk region. A gradual saturation of the electron traps occurs, leading to an increase in the electron diffusion length (10-20 times longer). This causes an increase in the bulk conductivity starting near the junction and extending deeper into the p-side bulk [8]. The voltage across the bulk is then lowered. That leads to the appearance of negative differential resistance region in the I-V characteristic (Fig.1). The necessary condition for switching to occur is that the lifetime of the minority carriers, (in our case electrons), to be much shorter than the majority carrier lifetime, at low injection conditions.

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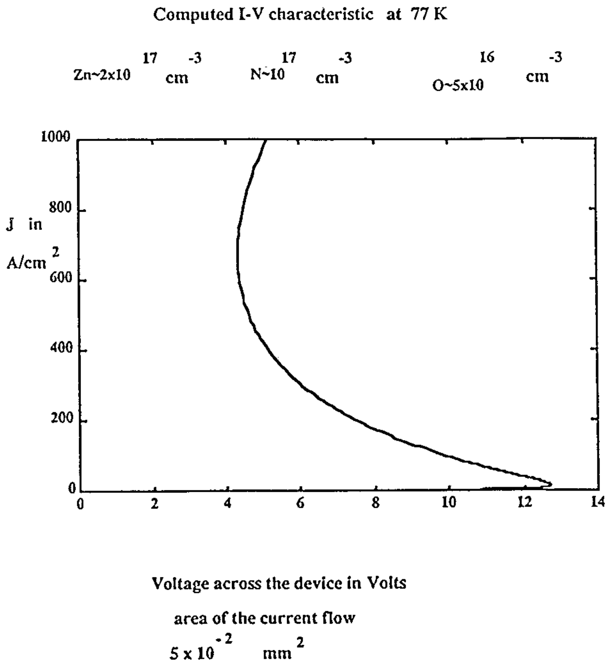


Fig.1

Modeling of the effect

The differential equations describing the rate of change in the number of free carriers and in the recombination centers are solved numerically. Recombination centers are considered to be those of Zn, O, Zn-O, and N in the p-side of the junction. Non-radiative recombination route is also allowed for each center. The rate equations used, together with the boundary conditions are the following:

$$\frac{dn}{dt} = G_n - R_n + \frac{1}{e}\frac{\partial J_n}{\partial z}$$

$$\frac{dp}{dt} = G_p - R_p - \frac{1}{e}\frac{\partial J_p}{\partial z}$$

$$\frac{dn_t}{dt} = R_n - R_p$$

$$R_n = \Sigma\, c_n\, n\,(N_t - n_t) - \Sigma\, e_n\, n_t\, N_c$$

$$R_p = \Sigma\, c_p\, p\, n_t - \Sigma\, e_p\,(N_t - n_t)\, N_v$$

$$\frac{dE}{dz} = \frac{e}{\varepsilon}[(p - p_o) - (n - n_o) - \Sigma\, n_t]$$

with

$$J_n = n\mu_n eE + kT\mu_n \frac{dn}{dz}$$

$$J_p = p\mu_p eE - kT\mu_p \frac{dp}{dz}$$

$$J = J_n + J_p$$

and boundary Conditions:

$$E = 0 \quad \text{at } z = 0$$

$$n = n_o \quad \text{at } z = L$$

$$n = n_o \exp(eV_j / akT) \quad \text{at } z=0, \qquad 1<a<2$$

$$p\,n = n_i^2 \exp(eV_j / kT) \quad \text{at } z=0$$

$$J(0)=J(L)$$

where c_p,c_n are the products $<\sigma_p v_{th}>$,$<\sigma_n v_{th}>$ of the capture cross sections and the thermal velocities of the carriers. N_t represents the concentrations of the recombination centers and traps, while n_t represents the number of electrons in the recombination centers and traps.

L is the length of the p-side bulk and n_o and p_o are the thermal equilibrium densities of the carriers. V_j is the potential drop across the junction and G_n,G_p represent the generation rates of free carriers.

In all cases

$\mu_n = 1200 \frac{cm^2}{sec}$ $\mu_p = 700 \frac{cm^2}{sec}$ $v_{th} \sim 5x10^6 \frac{cm}{sec}$ and $L=100\ \mu m$.

The parameters used for the various levels are:

$T \sim 77$ K.

O : $\sigma_n \sim 10^{-18}$ cm^2, $\sigma_p \sim 10^{-21}$ cm^2, $N_t \sim 10^{16}$ cm^{-3}

N: σ_n, $\sigma_p \sim 10^{-15}$ cm^2, $N_t \sim 10^{17}$ cm^{-3}

Zn-O: $\sigma_n \sim 2x10^{-16}$, $\sigma_p \sim 10^{-15}$ cm^2, $N_t \sim 10^{16}$ cm

Quasithermal equilibrium is assumed between the carriers and the corresponding bands. Interlevel transitions are not taken into account . The above assumptions are justified by the small dielectric relaxation time of the carriers, the non-degenerate doping and the strong spatial localization of the electron wavefunction in Zn-O, N and O levels.

The basic equations are put into discrete form by the finite difference technique using the Scharfetter-Gummel formulation [9],[10], and are solved by the Newton-Raphson method. Tolerance control, achieved with the use of an adaptive mesh size, is within 10^{-3} of the computed quantities. Solutions are obtained for the steady state. The doping concentrations and the device length are treated as parameters in the solution of the rate equations. The effect of relatively small changes in doping concentrations is shown in Fig. 2.

The presence of the strong Zn-O and N recombination routes does not screen out the O recombination route.This is mainly due to the larger thermal emission rates of N and Zn-O levels for electrons, as compared to those of the deep O level.

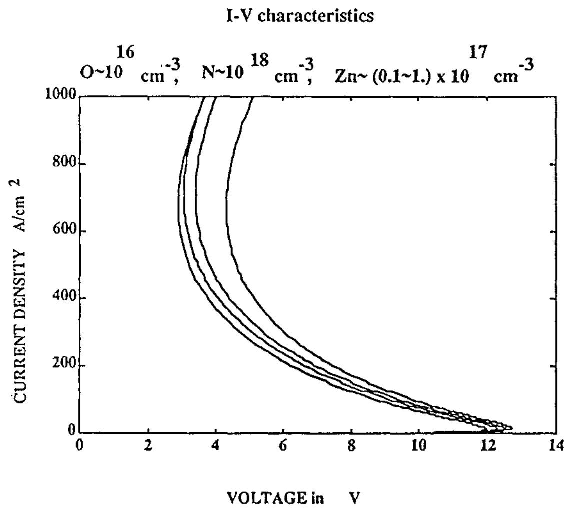


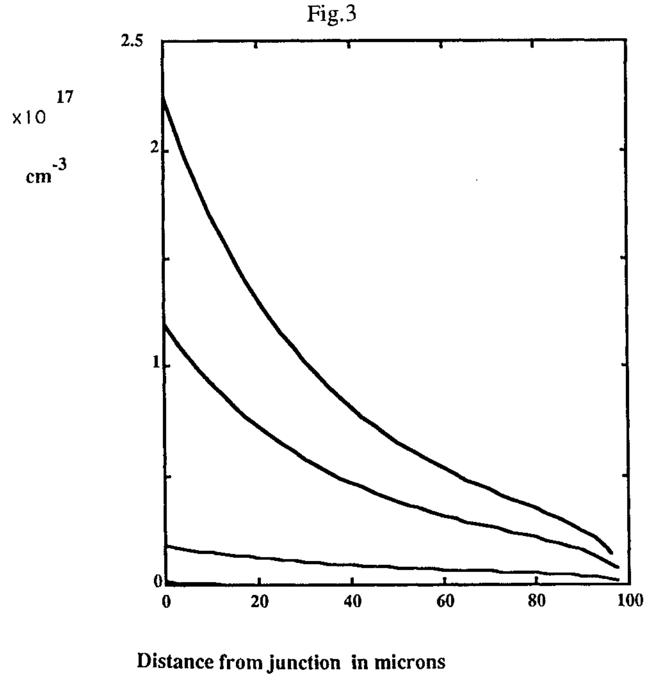
Fig. 2

The computed distributions of the electrons in the p-side bulk are shown in Fig. 3 for various current density levels. The critical current value or equivalently the critical voltage value depends on the degree of compensation, the type of dopants, and the length of the p-side bulk region. Optical feedback mechanisms and impact ionization of the various levels are considered to be, in our case, too weak to influence the breakdown conditions.

Minority carrier distribution in the p-side under various current density levels

Current density varies from 10 to 100 A/cm2
Recombination centers ~10 17 cm-3

Fig.3



<u>Transient Behavior</u>

The switching time between the low and the high conductance state is controlled by the applied voltage, the impurity species and their concentrations, and the optical energy of the trigger signal , as shown in Fig. 4 and Fig. 5 , for conditions appropriate for the experiments performed.

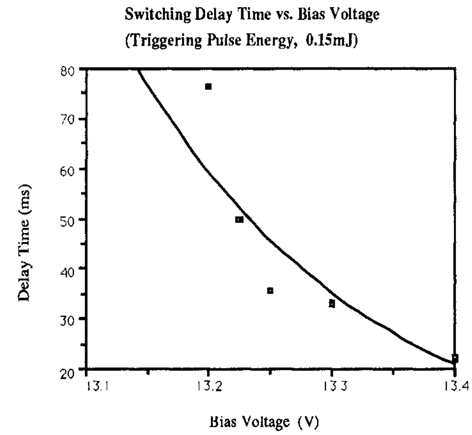


Fig. 4

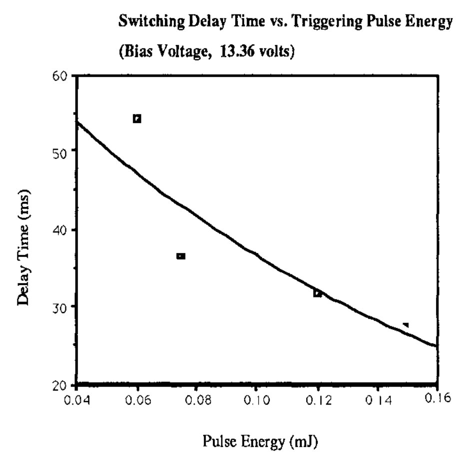


Fig. 5

Charge redistribution among the traps and the recombination centers during switching is the physical process which determines the delay time. The rise time is determined by the transit time of the electrons in the p-side bulk. The latter can be shorter than microseconds, implying a potential operation of the switch in the range of MHz. Optical triggering is achieved by creating more mobile carriers, increasing the conductivity of the diode, thus lowering the breakdown voltage (Fig. 6). Computed optical intensities of the order of 100 W / cm^2 at 2.35 eV are needed to lower the breakdown voltage by 50 mV. According to the model, when the concentration of the recombination centers is increased the switching to the high current state occurs at a higher bias voltage. The current density ranges up to 10^4 A/cm^2. This value can be improved by increasing the density of thermal equilibrium mobile carriers and the recombination component of the current. That can be achieved by increasing the doping of the n-side bulk, and the density of the recombination centers (N mainly) inside the junction.

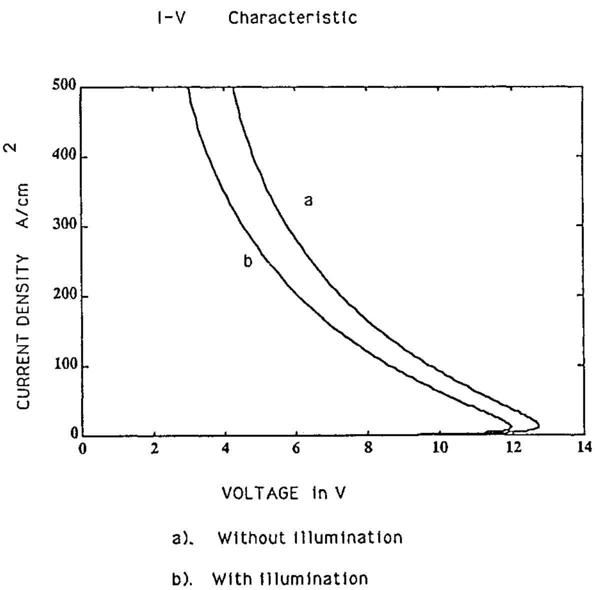


Fig. 6

Conclusion

The parameters involved in the diode-type switch were investigated. The switching action is based on the modulation of the base resistance in a GaP diode. From the analysis of the effect it occurs that the breakover voltage (.01-0.1 KV) increases with increasing the length of the base (in the range of 100-200 μm) and the density of shallow recombination centers $(1\text{-}10)\times10^{17}$ cm $^{-3}$. The forward voltage drop in the ON state can be reduced with increasing the doping (n or p type) concentrations. The current density ($\sim10^4$ A/cm^2), when the switch is in the ON state, increases with increasing the doping concentration, the density of the deep levels in the base, and shallow recombination levels inside the junction. The switching speed is increased with increasing the doping concentrations and decreasing the concentration of the deep, lifetime controlling, levels.

GaP is a suitable material for the realization of pulsed power switches based on the modulation of the base resistance. Its indirect bandgap makes it possible to control the carrier lifetimes (and consequently the dynamic resistance of the base) by properly choosing the impurity species and their concentrations. Advantages of this GaP diode-type switch include the simplicity of the p-n structure, the capability of optical triggering, the low power dissipation during switching, and the easy control of the doping profiles and device geometry.

Current research is aimed at achieving operation of the switch at room temperature by choosing the proper doping species and concentrations. In many semiconductor based switches, with bulk regions in the range of 10-200 μm, modulation of the base resistance can affect the performance of the switch sometimes in an unwanted way (early breakdown, large current, change in the operation point on the I-V characteristic). The presence of deep levels (controlling the free carrier lifetime) must be always taken into account in optimizing the performance of the switch.

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