HYSTERESIS AND BISTABILITY IN THE I-V CHARACTERISTICS OF P-N JUNCTIONS

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We study the problem of I-V characteristics of planar p-n junction from the view point of nonlinear dynamics. In order to evaluate analytically a kinetic function describing a charge balance of nonlinear system we propose a simple model of planar p-n junction and consider a possibility of observation of bistability and hysteresis. First of all the basic equations of planar p-n junction are nonlinear due to the generation-recombination term described by the Shockley-Read-Hall formalism, secondly origin of the nonlinearity is the Boltzmann distribution of the carriers. We determine a model of p-n junction by the next interpolation of generation-recombination rate

$$U(x)=\left[\{\frac{n(x)-n_{p0}}{\tau_1},[-d_1,-x_p]\},\{U_p+(U_0-U_p)\frac{x+x_p}{x_p},[-x_p,0]\},\{U_n-(U_n-U_0)\frac{x_n-x}{x_n},[0,x_n]\},\{\frac{p(x)-p_{n0}}{\tau_2},[x_n,d_2]\}\right] \quad (1)$$

and only consider direct charge pair recombination without a trapping. Here $U_p=\left(n(-x_p)-n_{p0}\right)/\tau_1$ and $U_n=\left(p(x_n)-p_{n0}\right)/\tau_2$. In steady state the parameter U_0 has to be found from the equation $U_0=U(0)$ with using of the Shockley-Read-Hall approximation at $x=0$. We consider idealized p-n junction structure with an abrupt doping step. Determination of model by equations (1) is considered as problem formulation. This gives us the facility to reduce a number of unknown quantities till to one $E_1=\frac{kT}{q}E(-d_1)$, where $E(-d_1)$ is the electric field applied to the p-side, and to transform the charge continuity equations into a single kinetic equation of type $\partial p_t=\partial n_t=f(E_1)=0$. Our model provides a solution of basic equations yielding an analytical expression for nonlinear kinetic function $f(E_1)$, balancing the incoming and outgoing of charges at the p-n boundary $x=0$. Continuity conditions for electron and hole currents together with continuity condition for electron concentration $n(x)$ and for hole concentration $p(x)$ at the interface $x=0$ leads to the system of four non-homogeneous linear algebraic equations. The Shockley equation with account of parasitic resistance can be derived from the system of these equations in the limit $U_0\to 0$. Solving these equations at $U_0\neq 0$ one obtains the parameter U_0 dependent on E_1 and V. To calculate the I-V characteristics of the planar p-n junction the parameter E_1 as a function of the bias voltage V must be evaluated numerically from the transcendental algebraic equation

$$\partial p_t = \partial n_t = f(E_1, V) = U_0(E_1, V) - U(0) = 0 \qquad (2)$$

On the basis of equations (1, 2) one can analyze the non equilibrium carrier and current densities, electric field strength and recombination-generation rate versus position x at various applied voltage.

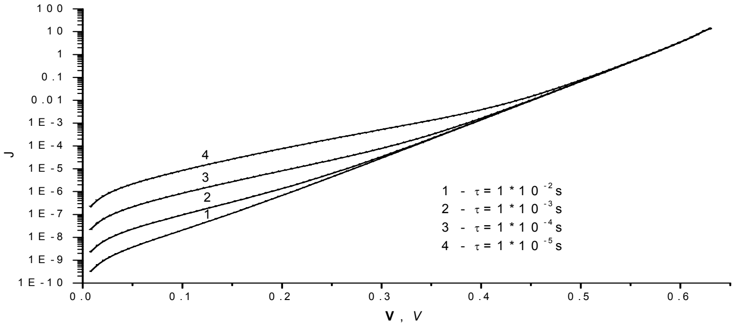

Fig.1. The dc forward I-V characteristics of the silicium p-n junction diode at T=300K, $N_d = 10^{21} m^{-3}, N_a = 10^{23} m^{-3}, \tau_1 = \tau_2 = 2.5 ms$ and different values of lifetime in depletion layer $\tau_n = \tau_p = 10\ ms$ (1), $1.0 ms$ (2), $0.1 ms$ (3), $10\ \mu s$ (4)

The I-V curves of the silicon p-n junction at different carrier lifetimes are displayed in Fig.1. The competition between recombination and diffusion contributions is evident. Recombination current dominates if the lifetime in the neutral region is much more than that in the depletion. Numerical results obtained for the I-V curves show that our model is in agreement with the experiment.

It is well known that nonlinear phenomena are associated with divergences of series of perturbation theory when small denominators occur. Analogous, solution of the system of our non-homogeneous algebraic equations exists if its determinant is non-zero. Using the set of parameters of Ge and substituting the numbers per unit volume of ionized impurities $N_d = 5 \cdot 10^{19} m^{-3}, N_a = 10^{23} m^{-3}$ and $d_1 = d_2 = 2 \cdot 10^{-5} m$ one obtains that system determinant is equal to zero at $E_{10} = 0.30558 m^{-1}$ independently of potential drop V in the range from $V = 0$ up to $V \cong 70$ mV.

Numerical calculations show that each function $f(E_1, V)$ graph crosses E_1 axis in the two points defining stationary states. Smaller value of E_1 defines stable steady state. Moreover, we can conclude that the instability increases at $E_1(V) \to E_{10}$. In the region $E_1(V) > E_{10}$ kinetic function has analogous features. In resulting, the I-V curve near the E_{10} has the form demonstrated in Fig.2. Stationary I-V characteristic as seen from the figure has two bifurcation points $E_1 = 0.2963\, m^{-1}, V = 52.8037$ mV and $E_1 = 0.316 m^{-1}, V = 54.7445$ mV.

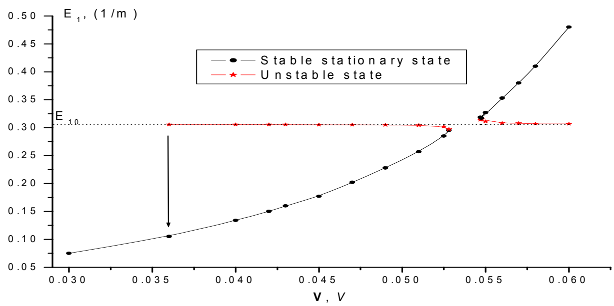

Fig.3. Bistability in current-voltage characteristics of a germanium $p^+ - n$ junction calculated at T=300K and $N_d = 5 \cdot 10^{19} m^{-3}, N_a = 10^{23} m^{-3}, \tau_1 = \tau_2 = 1.0 ms$

In the interval from one bifurcation point to another the solution of our equations does not exist, but transition from one bifurcation point to another is impossible. At the increase of the direct potential drop V the nonequilibrium phase transition is occurred from the state with n-type neutral region into the state in which current density is limited by the space-charge. At increasing of the bias voltage V, the all concentrations increase exponentially, but the value of ionized donors can not exceed the number of neutral donors. At high temperature the number of ionized shallow impurities is equal approximately to the number of neutral and in any case can not exceed it. Nonequilibrium phase transition is happened when supply of neutral donors or acceptors is exhausted. In the case of shallow donor impurity level $E_d = 0.05 E_g$ the phase transition point is at $V = 40$ mV. Here E_d is the impurity ionization energy, E_g is the band gap. Bifurcation point will be reached as applied voltage V is increased in magnitude, if the semiconductor germanium p-n junction diode has deep energy level impurities with $E_d \geq 0.6 E_g$. Decreasing the bias voltage one can move the system into the unstable state. Transition from the space-charge-limited-current phase to the neutral n-type region phase will be characterized by the hysteresis with negative differential resistance in the I-V curve of the $p^{+}-n$ semiconductor diode. The nonlinearity analyzed is due to the Boltzmann distribution of the carriers. Bistable states may be observed in the p-n junctions and heterostructures as in dark, or in load characteristics.