Study of Response of PIN Diode to Electromagnetic Pulse

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Abstract— Response of PIN diode is numerically simulated by a self-developed 2D semiconductor device simulation GSRES to study the response behavior of PIN diode limiter under electromagnetic pulse (EMP). Current overshoot phenomena of PIN diode during the rise time of EMP, which is validated to be due to the capacitive performance of PIN diode under high frequency, are analyzed. Shorter rise time of EMP causes higher current peak value. Overshoot current is affected by the impurity doping concentration of PIN diode. Higher doping concentration of impurity in the P layer and N layer causes higher peak of current and sooner attenuation of overshoot current. Doping concentration of the I layer affects the overshoot current too, but not as salient as concentration of the P and N layers. These results can be used in radiation hardening for PIN diode limiter.

Electronic systems are used more and more widely in industryeconomic and science research as key equipment. Semiconductor devices, as basic component, determines the performance of electronic system. Since the development of manufacturer techniques, operation power of device becomes much lower than before, and therefore, much more susceptive by electromagnetic pulse (EMP). For these reasons, study of the effects of semiconductor devices in electronic system under EMP is now becoming immediately demand not only for industrial application but also in informationize process. PIN diode, which is used as a component in communication and radar systems, is also the key component of PIN limiter, so the study of its effect under EMP is important in electronic equipment harding and shielding.

Comparing with experimental method, numerical simulation of semiconductor devices can reflect the physical phenomena and mechanisms of devices, and is important in effect study. It is proved to be efficient and accurate as many research results showed [1–3]. One-dimension numerical simulation result of PIN diode under step voltage pulses with risetime less than 0.1 ns is obtained [4] and overshoot current phenomenon appears. Characters of PIN diodes in EMP field are researched by equivalent circuit models [5, 6]. Also, abecedarian study of response of PIN diode under EMP is developped [7]. In this paper, relationship between overshoot current of PIN diode under EMP with the risetime of pulse and relationship between overshoot current of PIN diode under EMP with density of impurity of diode are studyed numerically by a simulator GSRES (General Semiconductor Radiation Effect Simulator).

1. INTRODUCTION OF SIMULATION METHOD

GSRES is now widely used in numerical simulation radiated field (EMP, HPM) effect of semiconductor device, which is developped by our research group. This simulator is assembled by modelling modular, meshing modular, data-base of material parameters and graphic vision modular. The numerical simulation of carriers bases on Drift-Diffusion Model (DDM). Two-dimension semiconductor device and simple circuit can be simulation numerically by this simulator [7–10].

Drift-Diffusion model is used more and more widely in numerical simulation of semiconductor device since the first use by Gummel. With out the consideration of the change of temperature, Poisson equation in double-carrier semiconductor device is

$$\nabla \cdot \varepsilon \nabla \psi = -q\left(p - n + N_D^+ - N_A^-\right) - \rho_s \tag{1}$$

where ψ is electrostatic potential, and in GSRES it is equivalent to vacuum energy level of electron. N_D^+ is the concentration of effective ionic donors, N_A^- is the concentration of effective ionic acceptor, and ρ_s is the static charge and interphase charge. Energy level of valence band and conduction band can be written up with ψ as

$$E_c = -q\psi - \chi + VE_c \tag{2}$$
$$E_v = E_c - E_g + VE_v \tag{3}$$

In equation, χ is electron affinity, VE_c and VE_v is the offset of energy band caused by heavily doped or internal stress. Electrostatic potential ψ is

$$\psi = \psi_{\text{intrinsic}} - \frac{\chi}{q} - \frac{E_c}{2q} - \frac{k_b T}{2q} \ln\left(\frac{N_c}{N_v}\right) \tag{4}$$

where $\psi_{\text{intrinsic}}$ is intrinsic Fermi potential. k_b is Boltzmann constant. N_c and N_v is the electron density of conduction band and valence band. Continuity equation of carrier is

$$\begin{cases} \frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n - (U - G) \\ \frac{\partial p}{\partial t} = \frac{1}{q}\nabla \cdot J_p - (U - G) \end{cases} \tag{5}$$

In Equation (5), J_n is the current density of electron. J_p is the current density of hole. U is the recombination term of carrier. G is the generation term of carrier. The current equation of J_n and J_p is

$$\begin{cases} J_n = q\mu_n n E_n + qD_n \nabla n \\ J_p = q\mu_p n E_p - qD_p \nabla p \end{cases} \tag{6}$$

where μ_n is mobility of electron and μ_p is mobility of hole. $D_n = \frac{k_b T}{q}\mu_n$ is the diffusion coefficient of electron and $D_p = \frac{k_b T}{q}\mu_p$ is the diffusion coefficient of hole. E_n is the equivalent electric field intensity to electron and E_p is the equivalent electric field intensity to hole. They can be expressed as

$$E_n = \frac{1}{q}\nabla E_c - \frac{k_b T}{q}\nabla\left(\ln(N_c) - \ln\left(T^{3/2}\right)\right) \tag{7}$$

$$E_p = \frac{1}{q}\nabla E_v + \frac{k_b T}{q}\nabla\left(\ln(N_v) - \ln\left(T^{3/2}\right)\right) \tag{8}$$

E_c is the electron energy level of conduction band and E_v is the electron energy level of valence band. If the temperature of lattice uniformity and invariablenes, gradient term of temperature is 0. Combining to Equations (1) and (5), the basic Drift-Diffusion model without temperature effect is

$$\begin{cases} \frac{\partial n}{\partial t} = \nabla \cdot \left(\mu_n n E_n + \mu_n \frac{k_b T}{q}\nabla n\right) - (U - G) \\ \frac{\partial p}{\partial t} = -\nabla \cdot \left(\mu_p p E_p - \mu_p \frac{k_b T}{q}\nabla p\right) - (U - G) \\ \nabla \cdot \varepsilon \nabla \psi = -q\left(p - n + N_D^+ - N_A^-\right) - \rho_s \end{cases} \tag{9}$$

Equation (9) is the basic and mostly used calculation model in GSRES. In our simulation, voltage amplitude loaded in diode is 0.9 V, and rise time is 100 ps, as showed in Fig. 2. The maximum current in the diode is 3.3336×10^{-4} A, which is normalized in Fig. 2. In this example, total Joule heat is about 1.23×10^{-15} J and the alteration of device's temperature is less than 0.01 K. So, although none thermal effect is contained in this model yet, the simulation result according with references and theoretical analysis quite well.

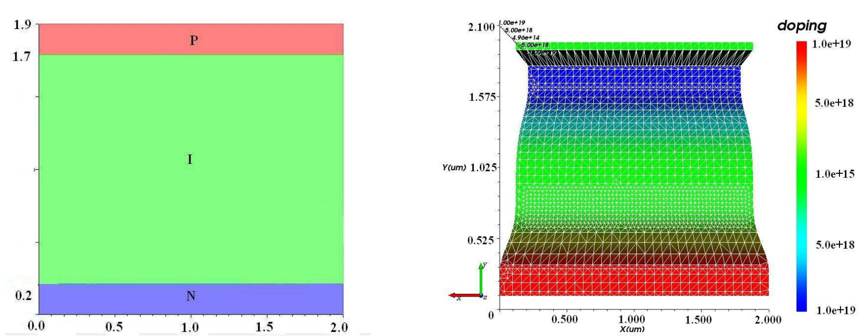


Figure 1: Two dimensional model of structure and doping density of PIN diode.

2. MODEL OF DEVICE

Figure 1 is a two dimensional model of a PIN diode, which is p^+nn^+ structure. The diode is uniformity in Z axis with a height of 1 μm. Width of this diode is 2 μm. Thickness of P layer an N layer are both 0.2 μm, with Gaussian doping both and peak density of impurity is $10^{19}\,\text{cm}^{-3}$. Diffusion width of P layer is 0.4 μm and N layer is 0.2 μm. I layer is as thick as 1.5 μm with a uniformity doping of $10^{15}\,\text{cm}^{-3}$ of acceptors.

3. SIMULATION RESULT AND DISCUSSION

3.1. Overshoot of Current under Electromagnetic Pulse

Effect of PIN diode under pulses with different risetime varying from 0.01 ns to 0.5 ns is studied using the numerical simulation method. The voltage pulse loaded in diode is step voltage with an amplitude of 0.9 V as showed in Fig. 2 (In Fig. 2 the rise time of pulse is 100 ps). The maximum current in the diode is 3.3336×10^{-4} A as referenced in part 1, and in Fig. 2 it is normalized.

As Fig. 2 shows, when voltage is rising, current in diode soon reaches to an great value; after risetime, voltage is steady and the current lows down to a small steady value. That is current overshoot phenomenon of PIN diode under EMP.

3.2. Relationship between Current Overshoot Phenomenon and Rise Time of Pulse

Current overshoot phenomenon appears because of the capacitance of PIN diode under the action from high frequency electromagnetic field of the pulse in risetime. Capacitive reactance relates with the frequency of the electromagnetic field which is induced by the rising edge of the pulse. Capacitive reactance becomes small when frequency increases. In this case, shorter the risetime of pulse is, higher the frequency is. So, Capacitive reactance of diode falls down when shorten the

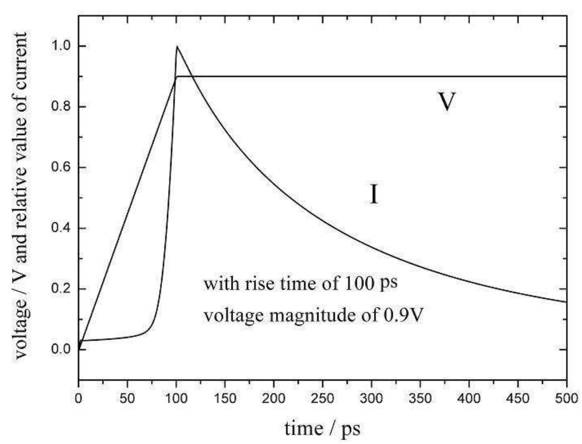


Figure 2: Behavior of current under EMP.

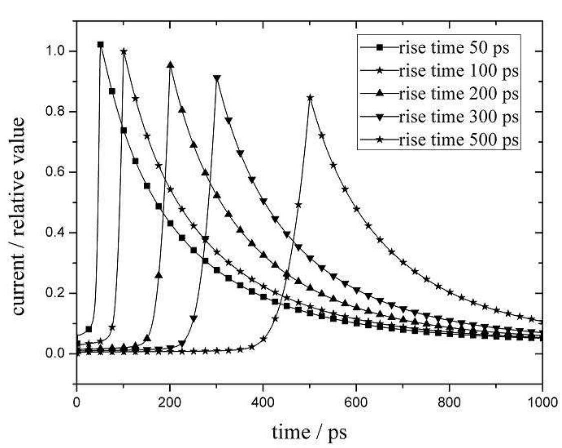


Figure 3: Behavior of current under EMP with varying rise time.

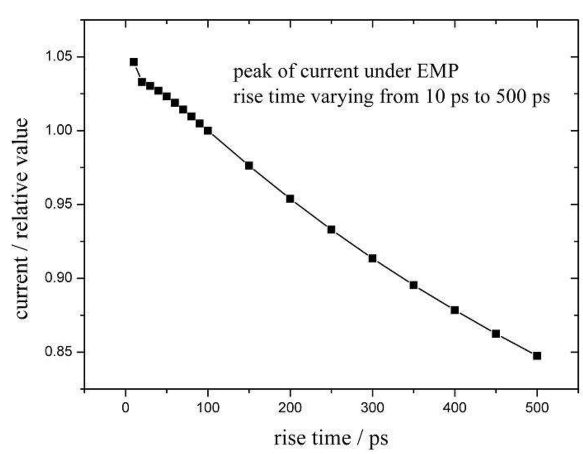


Figure 4: Peak of current under EMP with varying rise time.

risetime of pulse, and the peak value of overshoot current increases, as Fig. 3 showed. Pulse loaded in diode with amplitude of 0.9 V and risetime from 0.01 ns to 0.5 ns is showed in Fig. 3. Peak current of pulse with 0.01 ns risetime is higher than that of 0.5 ns and falls down faster than that of 0.5 ns too. Peak value of overshoot current in diode gives a nearly linearity relation with risetime as Fig. 4 shows.

3.3. Relationship between Current Overshoot Phenomenon and Density of Carriers

In this chapter, the density of impurity of the PIN diode is changed in order to analyse the response mechanism under EMP. The structure of diode is same as that in Fig. 1 but the doping densities of P layer and N layer are changed.

Current in different doping density PIN diodes loaded same pulse voltage with amplitude of 0.9 V and risetime of 0.1 ns is showed in Fig. 5 (In Fig. 5 current values are normalized). In each diode, the doping density of P layer is equal to that of N layer. Three diodes are simulated, the density of impurity of these diodes are $0.5 \times 10^{19}/\text{cm}^3$, $1.0 \times 10^{19}/\text{cm}^3$ and $2.0 \times 10^{19}/\text{cm}^3$. Peak value of current in the diode whose doping density is $2.0 \times 10^{19}/\text{cm}^3$ is greater than that in $0.5 \times 10^{19}/\text{cm}^3$ diode, and falls down more quickly than that in $0.5 \times 10^{19}/\text{cm}^3$ diode too. Behavior of current in $1.0 \times 10^{19}/\text{cm}^3$ diode is situated between that of the above two diodes. Peak value of overshoot current and falling down the speed are indicated to be related with the densities of carriers.

Peak values of overshoot current in these three diodes under voltage pulse with risetime from 0.01 ns to 0.1 ns are showed in Fig. 6(a) and risetime from 0.1 ns to 0.5 ns are showed in Fig. 6(b), the values are normalized in both two diagrams. Peak values of overshoot current are nearly linearly correlated with the periods of risetime according to Fig. 4. Slope of the linear fitting function of peak current values in the diode whose doping density is $2.0 \times 10^{19}/\text{cm}^3$ is greater than that in diode whose doping density is $0.5 \times 10^{19}/\text{cm}^3$ as Fig. 6 showed. This phenomenon suggests that the increase of doping density leads to not only the accretion of overshoot current but also the accretion of sensibility to the change of pulse waveform.

This phenomenon part l because the change of conductance induced by the varying of doping density. Current in the above three diodes under a 0.9 V stable voltage is showed in Table 1. Under stably voltage, while current is totally determined by conductance of diode, the variations between the three diodes are not the same comparing with that of pulse voltage. We suppose that the change of doping density inflects both conductance and capacitance of diode, thus influence the overshoot current.

Change of doping density in I layer inflects the current in diode too, but not as salient as that of P and N layers as Table 2 shows. Increase of doping density of I layer leads to the decrease of overshoot current. Discrepancy between current in diode with $0.1 \times 10^{19}/\text{cm}^3$ I layer doping density and current in $10 \times 10^{19}/\text{cm}^3$ diode is less than 3%. However, the change of doping densities of P and I layer from $1.0 \times 10^{19}/\text{cm}^3$ to $2.0 \times 10^{19}/\text{cm}^3$ cause an more than 40% change of current. Doping density of P layer and N layer influence the current in diode much more patently.

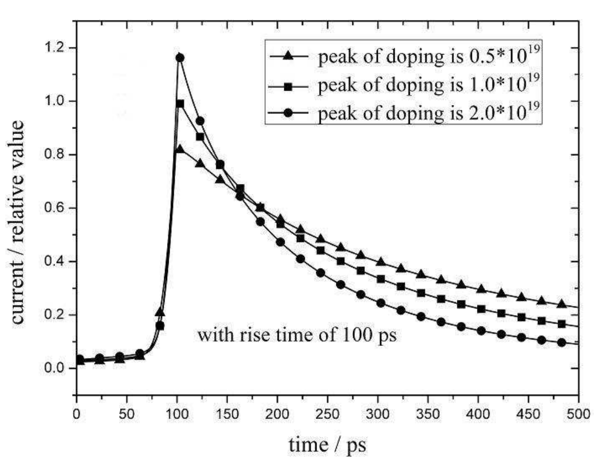
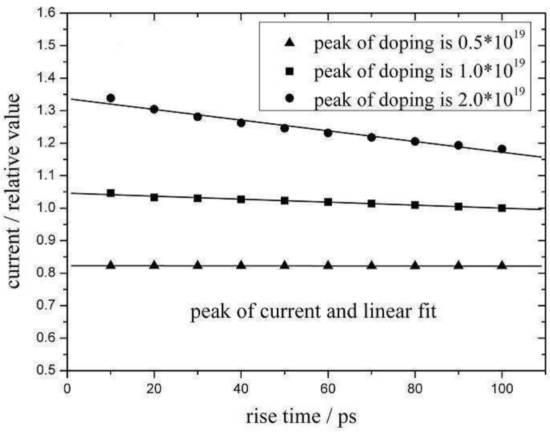
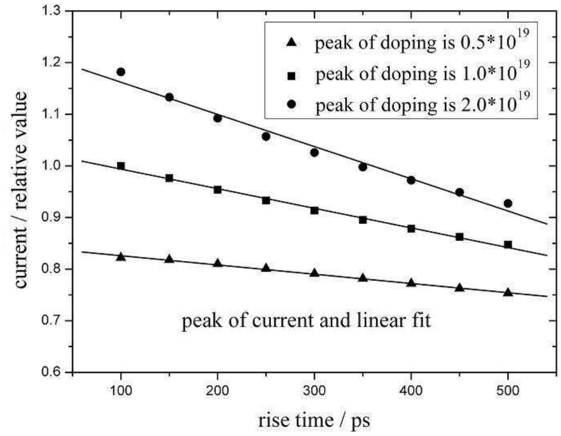


Figure 5: Behavior of current under EMP with varying doping concentration.



(a)



(b)

Figure 6: Peak of current under EMP with varying rise time in PIN diodes of different doping concentration, (a) with rise time varying from 10 ps to 100 ps, (b) with rise time varying from 100 ps to 500 ps.

Table 1: Current in PIN diode with varying doping concentration of P layer and N layer under 0.9 V stable voltage.

Doping density of P and N layer ($10^{19}/\text{cm}^3$)	Peak current under 0.9 V stable voltage (10^{-5} A)	Normalized value	Normalized peak current value under 0.1 ns risetime pulse	Normalized peak current value under 0.2 ns risetime pulse
0.5	1.1143	0.8145	0.8220	0.8493
1.0	1.3680	1	1	1
2.0	2.0053	1.4658	1.1820	1.1451

Table 2: Peak of current under EMP with varying doping concentration of I layer under EMP with risetime of 0.1 ns.

Doping density of I layer ($10^{15}/\text{cm}^3$)	Peak current under 0.9 V stable voltage (10^{-4} A)	Normalized value
0.1	3.3406	1.0021
0.5	3.3398	1.0019
1.0	3.3336	1
5.0	3.3035	0.9910
10	3.2675	0.9802

4. CONCLUSIONS

Current overshoot phenomenon appears in PIN diode because of the capacitance of diode under the action from high frequency electromagnetic field of the pulse in risetime. Capacitance of diode is influenced by doping density of P layer, N layer and I layer of diode and the frequency of loaded electromagnetic field. As simulation result shows, Peak value of overshoot current and the falling down speed are indicated to be negatively related with the densities of carriers in P layer and N layer almost linearly. Increase of doping densities in P and N layers leads to not only the accretion of overshoot current but also the accretion of sensibility to the change of pulse waveform. Doping density in I layer inflects the current in diode too, but not as salient as that of P and N layers.

Current overshoot phenomenon may causes a great transient current. If the risetime of pulse is short enough, transient current may interferes the signal in circuit or even leads to logical errors in circuits and causes the failture of electronic equipments. It is important in harding and shielding of electronic equipment. We plan to study the mechanism by analysing the causation of overshoot current using both numerical and experimental methods.

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