Comparison study of the charge density distribution induced by heavy ions and pulsed lasers in silicon*

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Abstract Heavy ions and pulsed lasers are important means to simulate the ionization damage effects on semiconductor materials. The analytic solution of high-energy heavy ion energy loss in silicon has been obtained using the Bethe-Bloch formula and the Kobetich-Katz theory, and some ionization damage parameters of Fe ions in silicon, such as the track structure and ionized charge density distribution, have been calculated and analyzed according to the theoretical calculation results. Using the Gaussian function and Beer's law, the parameters of the track structure and charge density distribution induced by a pulsed laser in silicon have also been calculated and compared with those of Fe ions in silicon, which provides a theoretical basis for ionization damage effect modeling.

Key words heavy ion, pulsed laser, charge density distribution

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1 Introduction

High energy heavy ions constitute less than 1% of cosmic rays [1], but they can cause serious damage to electric devices in spaceflight because of their high linear energy transfer (LET). When a high energy ion of several MeV/amu passes through a microelectronic-device in the space environment, it can interact with semiconductor materials and produce high-density electron-hole pairs (EHPs) along the ion track structure, which is an important way of inducing ionizing damage effects. The ground simulation of ionization damage effects on semiconductor materials consists of a heavy ion accelerator facility and a pulsed laser system. The interactions of heavy ions and pulsed lasers with semiconductor materials are intrinsically different, but both radiations may produce similar transient ionization effects in integrated circuits [2, 3]. In this paper we calculated the track charge density distribution induced by a 5 MeV/amu (285 MeV) Fe ion and a 1.064 μm pulsed laser in silicon, which provides a theoretical method for the pulsed laser simulation of the ionization damage effects of high energy ions in the space radiation environment.

2 Heavy ion energy loss and track charge density calculation in silicon

The energy loss of a heavy ion is described by the Bethe-Bloch formula [4]

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{4\pi z^2 e^4 N Z_{\mathrm{T}}}{m_{\mathrm{e}} v^2} \times \left[\ln\left(\frac{2m_{\mathrm{e}}v^2}{I}\right) - \ln(1-\beta^2) - \beta^2 - \frac{C}{Z}\right], \quad (1)$$

where z and v are the atomic number and velocity of the incident heavy ion, e and m_{e} are the electron charge and mass, N is the number of target atoms per cm^3, Z_{T} is the atomic number of the target atom. $\beta = v/c$, c is the speed of light in a vacuum, I is the mean excitation and ionization potential of absorber atoms, and I=9.76Z+58.8$Z_{\mathrm{T}}^{-0.19}$ [5] for Si. In Eq. (1), the second and third terms are the relativistic correction in the right square bracket. C/Z is the correction of the shell and it can be ignored for high energy heavy ion of MeV/amu.

According to the Bethe-Bloch formula, the energy distribution of the incident heavy ion with penetration depth d can be obtained

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$$E=E_0\left(2+\kappa-\frac{2\kappa}{1-\dfrac{1-\kappa}{1+\kappa}\exp\left[\dfrac{\kappa}{2}\left[-\dfrac{a}{E_0^2}d+\ln\left(1-\dfrac{3}{2\ln(bE_0)}\right)\right]\right]}\right), \tag{2}$$

where

$$\kappa=\sqrt{2\ln(bE_0)+1},\ a=\frac{\pi\rho N_\mathrm{A}Z_\mathrm{T}Z^{*2}e^4}{A}\frac{m}{m_\mathrm{e}},\ b=\frac{4m_\mathrm{e}}{mI},$$

N_A is Avogadro's number, m is the incident ion mass, A is the relativistic atomic mass of the target material. E_0 is the energy of the incident device surface, Z^* [6] is the effective charge number

$$Z^*=z\left[1-\exp\left(-\frac{125\beta}{z^{2/3}}\right)\right]. \tag{3}$$

To calculate the EHP two-dimension density distribution induced by heavy ions, the radial dose distribution $D(r)$ was required to be known. In Eq. (2), E is the dependence of the radial dose distribution $D(r)$ [7]:

$$D(r)=1.402\times E^{-0.887}r^{-\alpha} \quad 100\ \mathrm{nm}\leqslant r<1000\ \mathrm{nm}, \tag{4}$$

where $D(r)$ is in Gy(Si), r is the track radius, α=$2.7E^{-0.005}$ and E is in MeV/amu. Using Eq. (4), the track charge density distribution induced by a 5 MeV/amu Fe ion is calculated as shown in Fig. 1.

Figure 1 clearly shows that: (1) compared with the doping concentrations in silicon, the 5 MeV/amu Fe ion produces uniform and high-density EHPs along its track structure; (2) the radial EHP densities gradually decrease with increasing track radial, the EHP densities reduce from $8.0\times10^{21}/\mathrm{cm}^3$ at the track center to $7.70\times10^{20}/\mathrm{cm}^3$ at a radius of 1 μm.

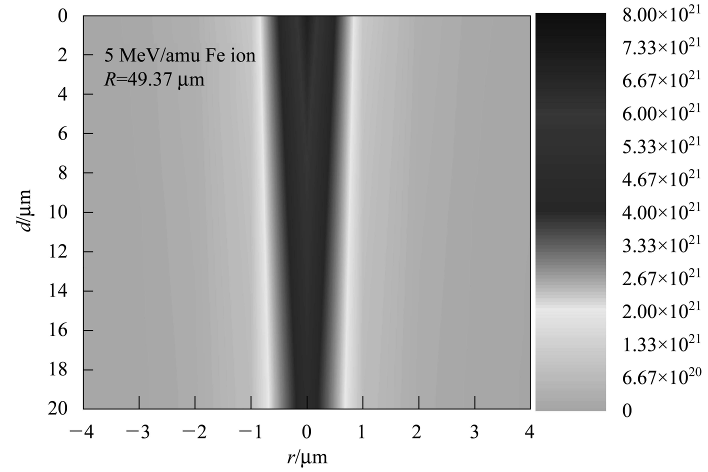

Fig. 1. The EHP density distribution induced by a Fe ion of 5 MeV/amu in silicon.

A more accurate radial EHP density distribution can be obtained by the model of Kobetich and Katz (KK theory)

$$\begin{aligned}N(t)\ =\ &\frac{1}{\varepsilon_\mathrm{ion}}\frac{\lambda}{s}\mathrm{e}^{-\left(\frac{qs}{r}\right)^p}\left[\left(1-\frac{s}{r}\right)p\left(\frac{q}{r}\right)^p s^{p-1}+\frac{1}{r}\right]\times\\ &\left[\ln\frac{r}{s}-\beta^2\left(1-\frac{s}{r}\right)+2\frac{\pi\beta Z^{*2}}{137}\left(1-\left(\frac{s}{r}\right)^{1/2}\right)-\right.\\ &\left.\frac{2}{3}\frac{\pi\beta Z^{*2}}{137}\left(1-\left(\frac{s}{r}\right)^{3/2}\right)\right],\end{aligned} \tag{5}$$

where r and s are the average range and the practical penetrating distance of an ejected electron, respectively, ε_ion is 3.6 eV, which is the mean energy to create an EHP by heavy ions,

$$q=0.0059Z_\mathrm{T}^{0.98}+1.1,\quad p=1.8(\log_{10}Z_\mathrm{T})^{-1}+0.31,$$

$$\lambda=\frac{NZ^{*2}e^4}{mc^2\beta^2}.\text{[8]}$$

Using Eq. (5), the radial density distributions induced by the Fe ion are calculated as shown in Fig. 2.

Figure 2 shows that: (1) when the track radius increases, the EHP densities will decrease for a specified energy heavy ion. As an example, for a 1 MeV/amu Fe ion, the EHP densities linearly reduce from $5.0\times10^{21}/\mathrm{cm}^3$ at a radius of 0.001 μm to $7.3\times10^{18}/\mathrm{cm}^3$ at a radius of 0.2 μm, and the EHP densities will reduce sharply with an excess of 0.2 μm; (2) the larger the heavy ion energy is, the larger the track radius is, but the lower the peak EHP density is. When the Fe ion energy increases from 1 MeV/amu to 10 MeV/amu, the track radius increases from 0.2 μm to 3.0 μm, but the peak EHP densities in the track center reduce from $5.0\times10^{21}/\text{cm}^3$ to $2.0\times10^{20}/\text{cm}^3$.

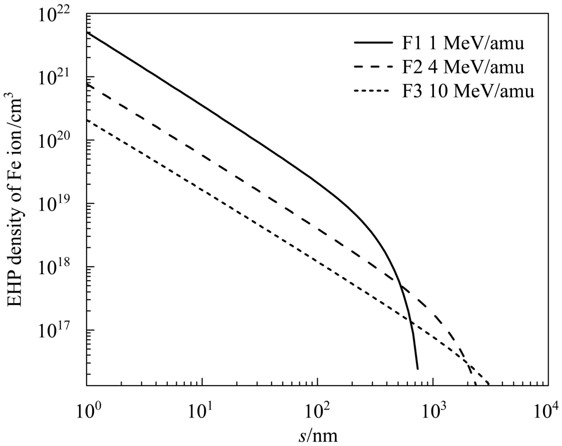

Fig. 2. Radial EHP density distribution induced by Fe ions calculated using the KK theory.

3 Pulsed laser energy-loss and track charge density calculation in silicon

Low energy photons excite the electrons from the valence band into the conduction band by the photoelectric effect. The transition probability of the electron depends on the photon energy ε_γ ($\varepsilon_\gamma=h\nu$, h is Plank's constant, and ν is the frequency of light). If the incident photon energy is larger than the semiconductor bandgap energy E_g (for silicon, E_g=1.1 eV), the photon will transfer its energy to an electron in the valence band, and the electron will rise from the valence band to the conduction band and create an EHP in its place. Under 1.064 μm pulsed laser irradiation, the electron in valence vertically transfers to a certain intermediate state firstly, and then relaxes to minimum energy state of the conduction band (X energy valley bottom) [9] as shown in Fig. 3.

The pulsed laser light intensity is described by the Gaussian function [10]

$$I(r,z)=\frac{P}{\pi\omega(z)^2/2}\mathrm{e}^{-\frac{2r^2}{\omega(z)^2}}\,, \tag{6}$$

where P is the pulsed laser power, r is a distance from the laser beam center, $\omega(z)$ is the beam radius, and is written as

$$\omega(z)=\omega_0\sqrt{1+\left(\frac{z}{z_0}\right)^2}\,, \tag{7}$$

where ω_0 is the laser radius at the surface, known as the beam waist, z is the propagation distance into the medium, and z_0 is the confocal length. In Eq. (6), P is given by [11]

$$P=\frac{E_\text{L}}{\sqrt{\pi}\,\tau}\,, \tag{8}$$

where E_L is the energy of the pulsed laser, and τ is the pulse width.

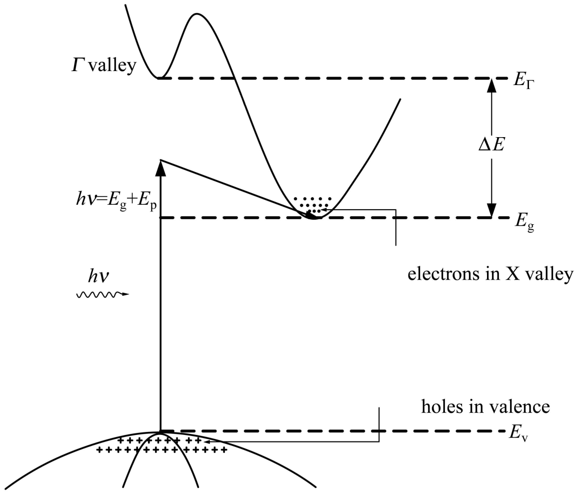

Fig. 3. Transition probability of an electron in the valence band in Si.

Under the linear absorption, the generation rate $g_\text{L}(r,z,t)$ of EHPs for a pulsed laser in silicon can be defined as

$$g_\text{L}(r,z,t)=\frac{1}{\varepsilon_\gamma}\frac{\mathrm{d}I(r,z)}{\mathrm{d}t\mathrm{d}z}\,, \tag{9}$$

where ε_r is the photon energy. In addition, the generation rate of EHPs is the spherical Gaussian function of time in the whole laser pulse width. According to Beer's law

$$\frac{\mathrm{d}I(r,z)}{\mathrm{d}z}=-\alpha I(r,z)\,, \tag{10}$$

where α is the linear optical absorption coefficient. $g_\text{L}(r,z,t)$ can be derived as

$$g_\text{L}(r,z,t)=\frac{2\alpha E_{\text{L}0}}{\pi^{3/2}\omega_0^2\varepsilon_\gamma\tau}\frac{\omega_0^2}{\omega(z)^2}\mathrm{e}^{-\frac{2r^2}{\omega(z)^2}}\mathrm{e}^{-\alpha z}\mathrm{e}^{-\frac{t^2}{\tau^2}}\,. \tag{11}$$

Using Eq. (11), the track charge density distributions induce by a 1 nJ 1.064 μm pulsed laser have been calculated as shown in Fig. 4 (ω_0 is assumed to be 1 μm).

Figure 4 shows that the radial EHP density distributions induced by the pulsed laser are more uniform than those induced by the heavy ion in a 1.4 μm radius, but the peak EHP densities induced by 1 nJ 1.064 μm pulsed laser energy are only $8\times10^{16}/\text{cm}^3$, which are much lower than those induced by the 5 MeV/amu Fe ion.

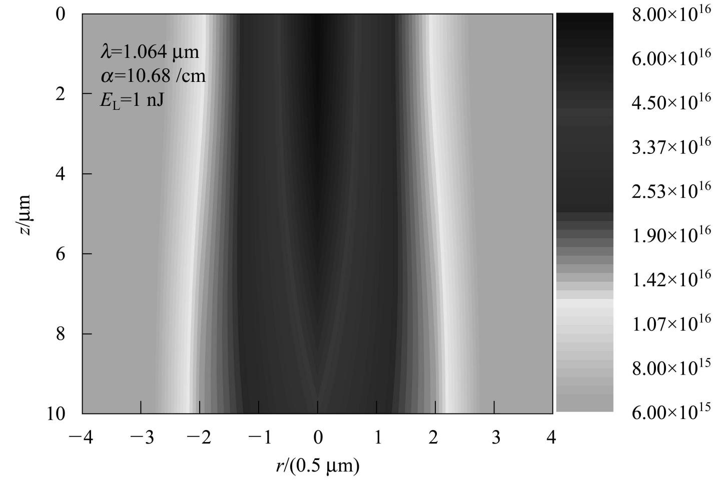

Fig. 4. The EHP density distribution induced by a laser pulse energy of 1 nJ for a wavelength of 1.064 μm in Si.

4 Conclusions

The heavy ion belongs to the deep penetration effect whose energy loss in a semiconductor is determined by its LET. The theoretical calculation illustrates that the radial FHP densities induced by a specified heavy ion energy in silicon will linearly decrease with the increase of the track radius. When the heavy ion energy increases, the track radius will be increased but the peak EHP densities in the track center will be decreased. The pulsed laser energy loss in a semiconductor decays exponentially with the penetration distance determined by Beer's law. The radial EHP density distribution induced by the pulsed laser is a typical wide-Gaussian distribution.

Comparison shows that the peaked radial charge densities are $7.5\times10^{20}/\mathrm{cm}^3$ and $8.0\times10^{16}/\mathrm{cm}^3$ for the Fe ion of 5 MeV/amu and the pulsed laser for a wavelength of 1.064 μm and a transmitted energy of 1 nJ, and the corresponding track radii are 1 μm and 1.4 μm. Though the difference between the heavy ion and the pulsed laser is 4 orders of magnitude, the track structures of both are very similar. Moreover, the penetration depth of a laser whose photon energy is close to the band gap of silicon can reach 1 000 μm because of the lower optical absorption in silicon. Therefore, the difference in the track structure becomes a minimum using the pulsed laser for a wavelength of 1.064 μm to simulate the ionization damage effects induced by high energy heavy ions.

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