СЕКЦИЯ 1
ПРОЦЕССЫ ВЗАИМОДЕЙСТВИЯ ИЗЛУЧЕНИЯ И ПЛАЗМЫ С ТВЕРДЫМ ТЕЛОМ

SECTION 1
PROCESSES OF RADIATION AND PLASMA INTERACTION WITH SOLIDS

MONTE CARLO SIMULATION OF CURRENT PHOTORESPONCE IN SILICON PHOTODIODE

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Ensemble Monte Carlo simulation of current photoresponse in silicon photodiode with p-n-junction under the effect of picosecond pulses of laser irradiation at 532 nm wavelength has been performed. The diode current photoresponse on the pulses of laser irradiation with $5{\cdot}10^{10}$ W/m^2 power density has been simulated for the lattice temperature of 300 K. The diode structures with different doping densities of p- and n- regions have been studied.

Keywords: Monte Carlo simulation; photocurrent; silicon photodiode.

Introduction

Silicon photodiodes, including avalanche ones, have now found wide application as converters of optical signals into electrical ones. Semiconductor photodiodes can be used as radiation detectors in the visible and infrared spectra and operate both in the conventional current mode and in the single photon counting mode [1, 2]. The great interest in silicon photodiodes is due, in particular, to the wide development of silicon technology in modern micro- and nanoelectronics, and, accordingly, the possibility of integrating such elements into various microelectronic systems within the framework of this technology for the production of integrated circuits.

Numerical simulation of the operation of photodiodes is currently an important task due to the need to predict the electrical characteristics of devices with given design and technological parameters, as well as to optimize these parameters in order to obtain the desired characteristics. To study the operating characteristics of photodiodes, a very effective method is numerical self-consistent simulation based on the ensemble Monte Carlo method [3-5]. This method is a powerful tool for the simulation of charge carrier transport processes in semiconductor device structures. The method makes it possible to calculate the electrophysical parameters and electrical characteristics, taking into account all significant charge carrier scattering processes, as well as the mechanisms of their generation and recombination. To adequately simulate the operation of diodes under reverse bias, it is necessary to take into account the physical processes that lead to the generation of charge carriers in the space charge region of the p-n junction. For submicron device structures and significant doping levels of their working regions, it is essential to take into account the processes of generation of charge carriers due to interband tunneling and avalanche multiplication due to impact ionization. Also, due to the presence of defects in the real crystal structure of silicon, the process of generation-recombination of charge carriers via traps can significantly affect the performance of the diode [6, 7].

In this paper, we present the results of numerical simulation of the current response of a silicon photodiode with a p-n junction under reverse bias to picosecond laser pulses in the visible range. We study the diode photoresponse for several values of the acceptor and donor doping levels of p- and n- regions.

Diode simulation model

Schematically the structure of the simulated silicon diode is presented in Fig. 1. The dimensions of the structure are as follows: the distance between electrodes L_C = 0.25 μm, the thickness of the structure — W_S = 0.5 μm. The length of the electrodes is 0.125 μm. The doping levels by donor impurity N_D and acceptor impurity N_A in the n- and p- regions vary from 10^{22} to 10^{23} m^{-3}. The lattice temperature is 300 K.

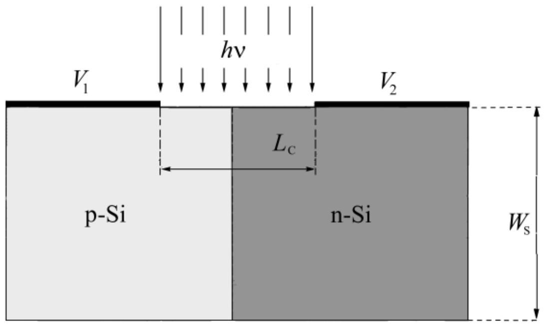

Fig. 1. Schematic cross section of the simulated silicon diode

The considered diode structure is simulated self-consistently in the framework of two-dimensional particle simulation. The general principles of particle simulations with application to semiconductors are described in [8]. The topology of the diode is such that the laser radiation is directed along the plane of the p-n junction and covers only the area between the electrodes. The p-n-junction plane is placed in the middle of the distance between the electrodes. The laser pulse duration is 1 ps. It is also assumed that the intensity of the radiation pulse is constant in time and uniform in space. The transport of electrons and holes is simulated taking into account the processes of scattering by optical and acoustic phonons, ionized impurities, plasmons, as well as the processes of optical generation and impact ionization. Also, the generation-recombination processes are included in the numerical transport simulation procedure in accordance with the models described in [6, 7, 9].

Results and discussion

Fig. 2 shows the dependences of the diode photocurrent density on time when the structure is irradiated with a single picosecond laser pulse. The radiation wavelength is 532 nm. Radiation power density — $5 \cdot 10^{10}$ W/m^2. In present work we regard a moderate reverse bias between the electrodes $V_2 - V_1$ = 5 V. It is assumed that the laser radiation is switched on at the time t = 1 ps. Prior to the onset of radiation exposure, a stationary mode of charge carrier transport in the diode is established at a given reverse bias on the electrodes with a reverse current equal to the value of the dark current. In the Fig. 2 curve 1 corresponds to the structure with $N_D = N_A = 10^{22}$ m^{-3}, curve 2 — N_D = 10^{23} m^{-3} and N_A = 10^{22} m^{-3}, curve 3 — N_D = N_A = 10^{23} m^{-3}.

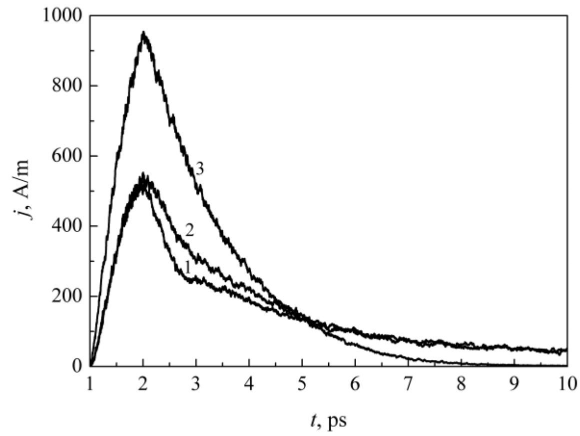

Fig. 2. The current photoresponse in the diode at reverse bias of 5 V for picosecond laser pulse at 532 nm wavelength and $5 \cdot 10^{10}$ W/m^2 power density

It follows from Fig. 2 that, for the structure under consideration, the decay time of the photocurrent after the end of exposure to radiation, during which the dark value of the current is established, is about 10 ps for the structure with doping density $N_D = N_A$ = 10^{23} m^{-3}, while for lower doping densities this time is longer. The higher peak current and faster decay at higher doping densities may be explained by higher electric field strength in the space charge region and, consequently, faster extraction of charge carriers from the region. Also, for the structure with $N_D = N_A = 10^{23}$ m^{-3} the impact ionization rate and avalanche multiplication of charge carriers, generated in the space charge region, is higher, thus contributing to the higher peak of the photocurrent. However, it should be noted that for the considered doping levels and voltage on the electrodes, the avalanche multiplication of charge carriers due to impact ionization is not significant enough and doesn't lead to avalanche breakdown of the p–n junction. Also, under considered simulation conditions the rates of other generation processes than photogeneration and avalanche multiplication don't make any appreciable effect on the diode current.

As shown by the calculations, the rate of current decay after exposure to radiation in diodes with a p-n junction under reverse bias is higher than in metal-semiconductor-metal silicon diode structures, which we considered earlier in [10], and significantly higher than in detectors based on submicron SOI MOSFETS considered in [11]. This can be explained by the fact that in the region of the space charge of the p-n junction, at a given distance between the electrodes and for the considered voltage values, a sufficiently high electric field strength is established, which contributes to the fastest extraction of the generated charge carriers from the working area of the device.

Conclusion

Numerical simulation based on the ensemble Monte Carlo method was used to study the current response of a silicon photodiode with a p-n junction exposed to a picosecond laser pulse with an intensity of $5 \cdot 10^{10}$ W/m^2 and a wavelength of 532 nm. The calculation results allow us to conclude that the shorter current decay time compared to such photosensitive structures as photodetectors based on silicon metal-semiconductor-metal structures and SOI MOSFETs is due to the presence of a sufficiently strong electric field in the space charge region of the p-n junction. At the same time avalanche multiplication of charge carriers in the space charge region of the diode is not sufficient enough at considered simulation conditions and doesn't make a sufficient influence on the photocurrent decay time.

References

1. Filachev A.M., Taubkin I.I., Trishenkov M.A. Tverdotel'naya fotoelectronika. Fotodiodi. Moskva: Fizmatkniga; 2011. 448 p. (in Russian).
2. Capasso F. Physics of avalanche photodiodes (In "Semiconductors and semimetals. Lightwave communication technology, vol 22, Part D. Photodetectors") / ed. by R. K. Willardson and A. C. Beer. Orlando: Academic Press; 1985. Ch. l, P. 2-168.
3. Moglestue C. Monte Carlo simulation of semiconductor devices. Springer; 1993. 334 p.
4. Aboud S., Saraniti M., Goodnick S., Brodschelm A., Leitenstorfer A. Full-band Monte Carlo simulations of photo excitation in silicon diode structures. *Semiconductor Science and Technology* 2004; 19: S301-S303.
5. Yanikgonul S., Leong V., Ong J.R., Png C.E., Krivitsky L. 2D Monte Carlo simulation of silicon waveguide-based single-photon avalanche diode for visible wavelengths. *Optics Express* 2018; 26(12): 15232-15246.
6. Hurkx G.A.M., Graaf H.C., Kloosterman W.J., Knuvers M.P.G. A new analytical diode model including tunneling and avalanche breakdown. *IEEE Transactions on Electron Devices* 1992; 39(9): 2090-2098.
7. Hurkx G.A.M., Klaassen D.B.M., Knuvers M.P.G. A new recombination model for device simulation including tunneling. *IEEE Transactions on Electron Devices* 1992; 39(2): 331-338.
8. Hockney R.W., Eastwood J.W. Computer simulations using particles. New York: McGraw-Hill; 1981. 640 p.
9. Jiao Y., Wei K., Wang T., Du G., Liu X. Comparison of band-to-band tunneling models in Si and Si-Ge junctions. *Journal of Semiconductors* 2013; 34(9): 092002-1-092002-5.
10. Borzdov A.V., Borzdov V.M. Monte Carlo simulation of silicon photodetector with metal-semiconductor-metal structure. Proceedings of the 14th International Conference «Interaction of Radiation with Solids» (September 21-24, 2021), Minsk. Minsk: BSU; 2021. P. 23-25.
11. Borzdov A.V., Borzdov V.M., Vyurkov V.V. Monte Carlo simulation of picosecond laser irradiation photoresponse of deep submicron SOI MOSFET. *Proceedings of SPIE* 2022; 12157: 121570Y-1-121570Y-6.