Electrostatics of the nanowire radial *p-i-n* diode

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Abstract. In this paper, the electrostatic theory of the nanowire radial core-shell *p-i-n* homojunction has been considered. The carried out calculations show that, in contrast to planar *p-i-n* diode, the built-in electric field of the nanowire radial *p-i-n* diode proves to be inhomogeneous. This field reaches its maximum in the region of the *i*-layer adjoining to the core. When moving away the *i*-layer from the nanowire center, the degree of field inhomogeneity decays, and both edge values of the field in the *i*-layer reach eventually the magnitude, which takes place in analogous planar *p-i-n* diode. This magnitude can be both higher and lower than the maximal field in the nanowire *p-i-n* diode (depending on doping conditions). Simultaneously, the capacitance of the nanowire *p-i-n* diode can both increase and decrease in its value, going, at the same time, to weak voltage dependence inherent to the planar *p-i-n* diode.

Keywords: nanostructures, core-shells nanowire, radial *p-i-n* junction, capacitance.

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1. Introduction

In the recent time, a great interest of the investigators is attracted to semiconductor nanowires, especially to the multilayer ones, whose layers are either doped in different ways or form a heterostructure. On the base of these objects, principally new constructions of the core-shell devices are created, which use both transverse (radial) transport of the current carriers (radial solar cells [1], radial photodiodes [2], radial light emitting devices [3]) and their longitudinal transport (field-effect transistor [4], high electron mobility transistor [5]).

Cylindrical symmetry inherent to these nanostructures introduces a number of peculiarities to their electrophysical properties. In particular, depletion widths of the radial *p-n* junction depend on its radius in a rather nonstandard way: as radius of the *p-n* junction decreases, depletion width of the core increases [6], but that of the shell, on the contrary, decreases [7, 8]. As a result, in the devices where the heterostructure *p-n* junction is used, this fact results in changing the relative contribution to the device performance characteristics from different constituent materials. Namely, the lesser radius of the heterostructure *p-n* junction, the larger is contribution from the core material.

In the radial *p-n* junction, the dependence $1/C^2$ versus U (C is the barrier capacitance, U – applied voltage) proves to be nonlinear [6, 8]. Furthermore, strong asymmetry in injection from the core to shell and from the shell to core appears [9].

These studies concern nanowire *p-n* junction structures. At the same time, radial nanowire structures use often not *p-n* but *p-i-n* junctions [10-14]. In particular, this makes it possible to broaden the region of strong electric field in the junction, which is additional advantageous in materials with short minority carrier diffusion lengths [15]. Electrostatics of these structures was not studied so far. In this paper, electrostatics of the radial *p-i-n* homojunction has been investigated theoretically.

2. Theory

Schematic view of the structure under consideration is presented in Fig. 1. Here r_p is the depletion region boundary in the core, r_n – depletion region boundary in the shell, and *i*-layer is located between r_1 and r_2.

In the depletion approximation, we have Poisson's equations

$$\frac{1}{r}\frac{d}{dr}(rE) = \frac{qN_A}{\varepsilon_S}, \qquad r_p \le r \le r_1, \tag{1a}$$

$$\frac{1}{r}\frac{d}{dr}(rE) = 0, \qquad r_1 \le r \le r_2, \tag{1b}$$

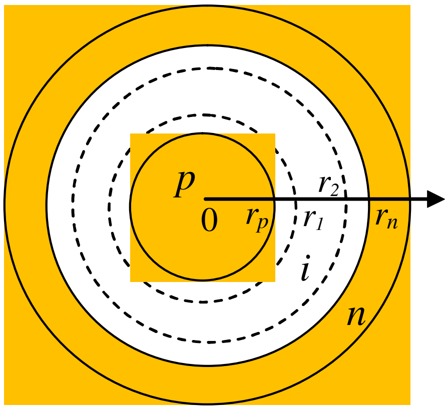

Fig. 1. Schematic view of the nanowire structure under consideration.

$$\frac{1}{r}\frac{d}{dr}(rE) = -\frac{qN_D}{\varepsilon_S}, \qquad r_2 \le r \le r_n, \qquad (1c)$$

where q is the electron charge, ε_S – dielectric constant of the semiconductor, N_A and N_D are the concentrations of acceptors and donors, respectively. Solution of these equations gives the electric field distribution in the structure

$$E = -\frac{qN_A}{2\varepsilon_S}\frac{r^2 - r_p^2}{r}, \qquad r_p \le r \le r_1, \qquad (2a)$$

$$E = \frac{A}{r}, \qquad r_1 \le r \le r_2, \qquad (2b)$$

$$E = \frac{qN_D}{2\varepsilon_S}\frac{r^2 - r_n^2}{r}, \qquad r_2 \le r \le r_n, \qquad (2c)$$

where A is the integration constant.

Matching the electric fields at r_1 and r_2, we obtain

$$A = -\frac{qN_A}{2\varepsilon_S}\left(r_1^2 - r_p^2\right) = \frac{qN_D}{2\varepsilon_S}\left(r_2^2 - r_n^2\right), \qquad (3)$$

whence it follows

$$N_A\left(r_1^2 - r_p^2\right) = N_D\left(r_n^2 - r_2^2\right). \qquad (4)$$

The second integration of Eq. (2) gives the potentials

$$V(r) = \frac{qN_A}{2\varepsilon_S}\left(\frac{r^2 - r_p^2}{2} + r_p^2 \ln\left(\frac{r_p}{r}\right)\right), \qquad r_p \le r \le r_1, \qquad (5a)$$

$$V(r) = -A\left(\ln(r) + \text{const}\right), \qquad r_1 \le r \le r_2, \qquad (5b)$$

$$V(r) = -\frac{qN_D}{2\varepsilon_S}\left(\frac{r^2 - r_n^2}{2} + r_n^2 \ln\left(\frac{r_n}{r}\right)\right) + V_{bi}, \qquad r_2 \le r \le r_n, \qquad (5c)$$

where the following boundary conditions are used

$$V(r_p) = 0, \qquad V(r_n) = V_{bi}, \qquad (6)$$

V_{bi} is the built-in potential of the junction. Matching of the potentials at $r = r_1$ and $r = r_2$ allows us to exclude const and obtain equation

$$\frac{qN_A}{2\varepsilon_S} r_p^2 \ln\left(\frac{r_p}{r_1}\right) + \frac{qN_D}{2\varepsilon_S} r_n^2 \ln\left(\frac{r_n}{r_2}\right) - A\ln\left(\frac{r_2}{r_1}\right) = V_{bi}. \qquad (7)$$

Equations (4) and (7) have to be solved jointly in order to obtain r_p and r_n. All the rest quantities are expressed through them.

The barrier capacitance $C = \frac{dQ_p}{dU}$, where Q_p is the electric charge concentrated in the depleted p-region of the junction. This charge is given by

$$Q_p = qN_A\pi\left(r_1^2 - r_p^2\right)L \qquad (8)$$

where r_p is voltage-dependent and L is length of the nanowire. Inasmuch as

$$\frac{dr_p}{dU} = \frac{\varepsilon_S}{qN_A r_p}\frac{1}{\ln\left(r_n/r_p\right)}, \qquad (9)$$

the capacitance per unit area of the p-i-n junction is

$$C = \frac{\varepsilon_S}{r_1}\frac{1}{\ln\left(r_n/r_p\right)}. \qquad (10)$$

3. Numerical results

For numerical solution of Eqs. (4) and (7), the parameters of silicon at room temperature have been chosen. Three doping situations have been considered: $N_A = N_D$, $N_A >> N_D$, and $N_A << N_D$. The calculation results for the electric field distribution in the structure are presented in Fig. 2. The characteristic feature of these distributions is inhomogeneity of the field in the i-layer, which sharply differs from the case of planar p-i-n diode, where electric field in the i-layer is homogeneous [16]. The field inhomogeneity is especially strong when $N_A = N_D$ or $N_A >> N_D$ and diminishes with thickening of the i-layer. In any case, the electric field is maximal near the nanowire core.

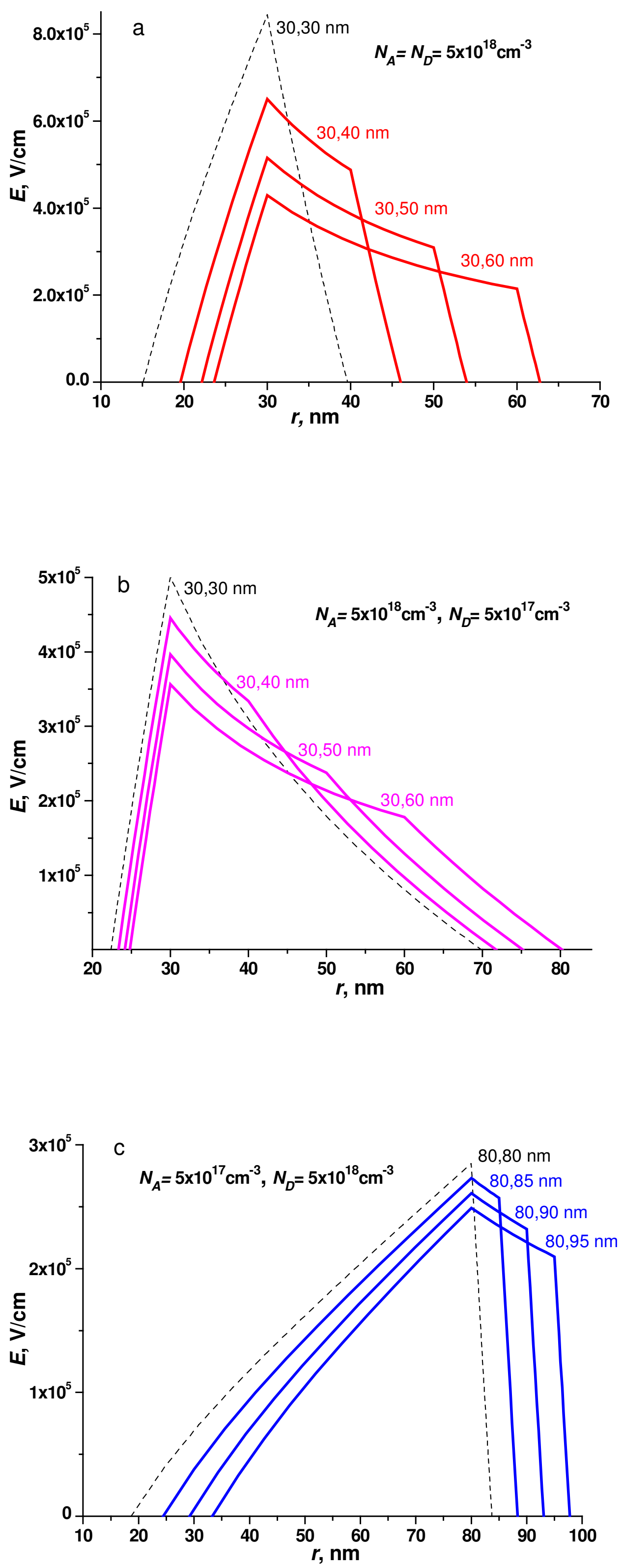

Fig. 2. Electric field distribution in the nanowire *p-i-n* diode at $N_A = N_D$ (a), $N_A >> N_D$ (b), and $N_A << N_D$ (c); numbers near the curves are radial coordinates of the *i*-layer showing its extent, dashed lines corresponds to the *i*-layer of zero extent (*p-n* diode).

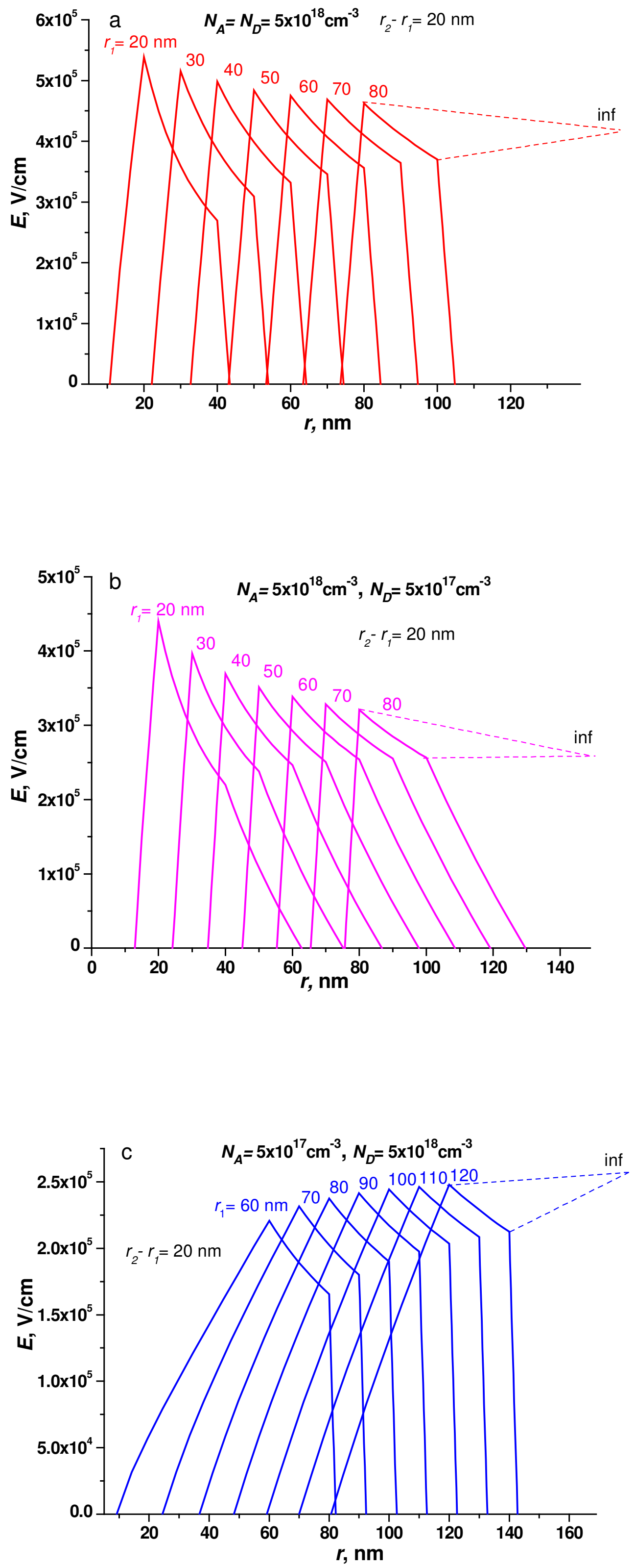

Fig. 3. Electric field distribution in the nanowire *p-i-n* diode depending on radial position of the *i*-layer at $N_A = N_D$ (a), $N_A >> N_D$ (b), and $N_A << N_D$ (c); dashed lines shows to what magnitude both edge values of the field in the *i*-layer go, when the nanowire *p-i-n* diode becomes the planar one.

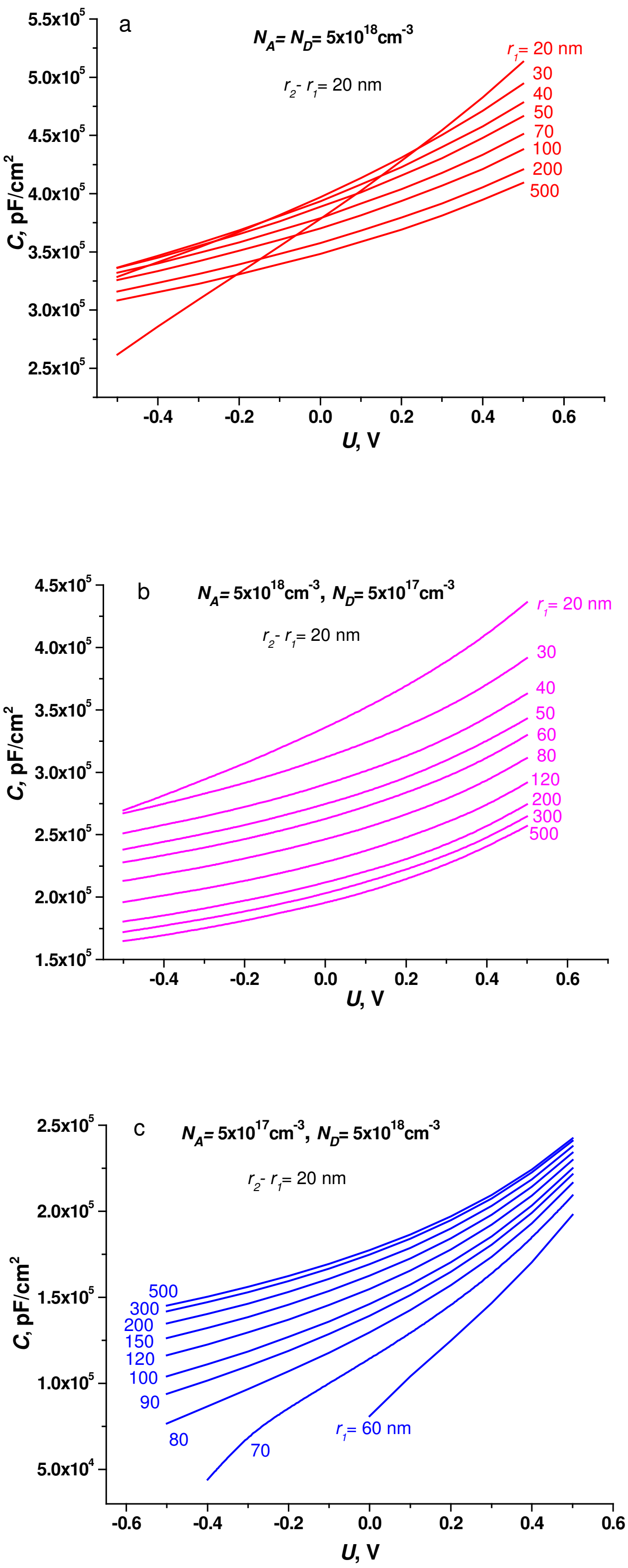

Fig. 4. Voltage dependences of the nanowire *p-i-n* diode capacitance at $N_A = N_D$ (a), $N_A >> N_D$ (b), and $N_A << N_D$ (c) as a function of the distance between the *i*-layer and the nanowire center.

It is of interest to study dependence of the electric field distributions on radial position of the *i*-layer in this nanowire. Fig. 3 represents such dependences for three doping situations at the same thickness of the *i*-layer equal to 20 nm. It is seen that, as the *i*-layer moves away from a center of the nanowire, inhomogeneity of the electric field distribution becomes more and more weak, *i.e.*, the field goes to homogeneous one inherent to planar *p-i-n* diodes.

The dash lines in these figures demonstrate asymptotical confluence of both edge values of the field in the *i*-layer, when r_1 goes to infinity, *i.e.*, the nanowire curvature becomes ignorable. It is seen also that the maximum electric field in the *i*-layer of nanowire proves to be higher than that in an analogous planar diode at $N_A = N_D$ and $N_A >> N_D$ and, on the contrary, is lower at $N_A << N_D$.

Fig. 4 represents the voltage dependences of the nanowire *p-i-n* diode capacitance given by the formula (10) for three doping combinations as a function of the distance between the *i*-layer and center of the nanowire at the same value of the *i*-layer thickness equal to 20 nm.

As it follows from these figures, the capacitance of the nanowire *p-i-n* diode decreases with moving away the *i*-layer from the nanowire center at $N_A = N_D$ and $N_A >> N_D$ and, on the contrary, increases at $N_A << N_D$. In any case, the voltage dependence of the capacitance diminishes as it has to be in planar *p-i-n* diode [16].

4. Conclusions

Being used as solar cells or photodiodes, the nanowire radial *p-i-n* diodes have certain advantages as compared with the planar analogs. In particular, at $N_{core} = N_{shell}$ or $N_{core} >> N_{shell}$, the maximal built-in electric field in the *i*-layer proves to be higher than that in planar *p-i-n* diode under other equal conditions. But one has to keep in mind that the highest electric field is localized in the region of the *i*-layer adjoining to the core. It should be also noted that the capacitance of the nanowire *p-i-n* diode can be both larger and smaller than that of its planar analog at the same parameter values.

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