Differential Capacitance of a $p^+-p$ Junction

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Abstract — The differential capacitance of a $p^+-p$ junction formed by charge redistribution near the junction, has been investigated taking into account the electric field in the quasi-neutral $p$ region. The dependence of the capacitance and current of the $p^+-p$ junction on its voltage is obtained. It is shown that a change in the sign of the $p^+-p$-junction capacitance with an increase in the injection level is caused by a decrease in the bipolar drift mobility in the $p$-type region. It is also demonstrated that a change in the sign of the $p^+-p$-junction capacitance with an increase in the reverse voltage determines the charge reduction near the junction, as the increase in the negative charge of acceptor ions predominates over the increase in the positive charge of holes.

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1. INTRODUCTION

It was experimentally shown in [1] that the character of the current dependence of the differential capacitance of germanium $p^+-p$ junctions with close-to-intrinsic conductivity of the $p$-type region changes with an increase in the junction temperature. At the temperature $T = 300$ K, the capacitance of a $p^+-p$ junction increases with an increase in the forward current, and changes the sign from positive to negative with an increase in the reverse current. At temperatures $T \geq 310$ K, the $p^+-p$-junction capacitance reaches its maximum with an increase in the forward current, and then decreases and changes sign. The theory of $h-l$ junctions [2–6] cannot explain this change in the character of the current dependence of the $p^+-p$-junction capacitance when the junction temperature is increased.

In this context, our purpose was to investigate the dependences of the differential capacitance and current of the $p^+-p$ junction on the junction voltage. The $p^+-p$-junction capacitance, formed by charge redistribution in the junction region, is considered taking into account the change in the electric field in the quasi-neutral $p$-type region in both forward- and reverse-bias modes. The field in the quasi-neutral $p$-type region of a forward-biased $p^+-p$-junction is determined with the dependence of bipolar drift mobility on the concentration of nonequilibrium electron–hole pairs taken into account.

It is shown that the change in the character of the dependence of the $p^+-p$-junction capacitance on the injection current with an increase in the junction temperature is due to a decrease in the bipolar drift mobility in the $p$-type region when the conductivity of the latter becomes close to intrinsic one.

It is also shown that the change in the sign of the $p^+-p$-junction capacitance with an increase in the reverse current is caused by charge reduction in the junction region due to the dominance of the increase in the negative charge of acceptor ions over the increase in the positive charge of holes.

2. DYNAMIC EQUILIBRIUM EQUATIONS FOR $p^+-p$ JUNCTION

The distributions of the electric field and potential in the space-charge region (SCR) of $n^+-n$ and $p^+-p$ junctions in thermodynamic equilibrium were analyzed in [7–11]. A method for obtaining exact field and potential distributions in the SCR of a $p^+-p$ junction in thermodynamic equilibrium was proposed in [11] (see figure).

Energy-band diagram of a $p^+-p$ junction: $\varepsilon_c$ is the bottom of the conduction band, $\varepsilon_v$ is the top of the valence band, $\varphi_k$ is the potential barrier of the junction region, and $L_0$ is the junction width.
The electron charge in the SCR of a $p^+–p$ junction is much lower than that of holes. Therefore, electron–hole recombination in the SCR can be disregarded. In this case, the hole and electron currents in the SCR are independent of coordinate $x$. The dynamic-equilibrium state of a $p^+–p$ junction is determined by the system of equations

$$\frac{j_n}{qD_n} = \frac{p(x) \frac{d\phi(x)}{dx} - dp(x)}{kT dx},$$

$$\frac{j_p}{qD_p} = \frac{n(x) \frac{d\phi(x)}{dx} + dn(x)}{kT dx},$$

$$\frac{d^2\phi(x)}{dx^2} = \frac{4\pi q^2}{\varepsilon} [p(x) - (p_T - n_T) - n(x)],$$

along with the dynamic-equilibrium condition for the SCR. Here, $j_n$ and $j_p$ are the hole and electron currents, respectively; $p(x)$ and $n(x)$ are the distributions of holes and electrons, respectively; $p_T$ and $n_T$ are the hole and electron concentrations in the $p$ region in thermodynamic equilibrium; $\phi(x) = -q\psi(x)$ ($q$ is the elementary charge and $\psi(x)$ is the positive potential); $k$ is the Boltzmann constant; $T$ is the temperature (in kelvins); $\varepsilon$ is the permittivity of the semiconductor lattice; and $D_n\mu_n = D_p\mu_p = kT/q (D_p$ and $D_n$ are the hole and electron diffusion coefficients, respectively; and $\mu_p$ and $\mu_n$ are the hole and electron mobilities).

The boundary conditions for the system of equations (1)–(3) can be written as

$$\phi(L) = 0,$$  

$$\phi(0) = q(U_k \mp U),$$  

$$p(L) = p_L,$$  

$$p(0) = p_0(0) \pm \Delta p(0)$$

$$= p_T e^{\frac{qU_0}{kT}} \left[ 1 \pm \Delta p(0) \right],$$

$$n(L) = n_L,$$  

$$n(0) = n_0(0) \pm \Delta n(0)$$

$$= n_T e^{\frac{qU_0}{kT}} \left[ 1 \pm \Delta n(0) \right].$$

$$n(0) = n_L e^{\frac{q(U_k \mp U)}{kT}} \mp \Delta n(0),$$

$$\left( \frac{d\phi(x)}{dx} \right)_{x=L} = \left( \frac{d\phi(x)}{dx} \right)_{L+0}.$$  

Here, $L$ is the junction (SCR) width; $U$ is the voltage corresponding to the potential difference $U_k$; $p_0(0)$ and $n_0(0)$ are, respectively, the hole and electron concentrations in thermodynamic equilibrium (the upper and lower plus and minus signs indicate, respectively, cases of forward and reverse biasing); and $q^{-1}\frac{d\phi(x)}{dx} = E(L)$ is the electric field. The parameters $p_L, n_L, \Delta p(0), \Delta n(0)$, and $[d\phi(x)/dx]_L$ depend on voltage $U$.

Having presented $\Delta n(0)$ in the form (9) and (10), one can express $\Delta n(0)$ in terms of $n_L$.

The first term on the right-hand side of condition (10) is the electron concentration near the surface of the $p^+$ region when the electron distribution in the SCR with $U_k \mp U$ obeys the Boltzmann law. Note that condition (10) can only be used when replacement of the distribution $n(x)$ with the Boltzmann distribution causes a negligible change in $U_k \mp U$.

The relationship between the $n_T$ and $p_T$ concentrations determines the quasineutrality condition of the $p$ region, which has the following form on the SCR boundary at $x = L$:

$$n_L = n_T \pm \Delta p(L) = n_T + (p_L - p_T).$$  

Here, $p_L - p_T > 0$ and $p_L - p_T < 0$ for forward- and reverse-biased junctions, respectively.

The $\Delta p(0)$ value is determined by the quasineutrality condition of the $p^+$ region. Near the surface of this region ($x = 0$), the quasineutrality condition can be written as

$$\Delta p(0) = \Delta n(0).$$

Boundary condition (11) shows that the electric field at the interface between the SCR and quasineutral $p$ region of the junction is nonzero in both forward- and reverse-bias modes.

In the case of a forward-biased $p^+–p$ junction, the electric fields of the SCR and the quasineutral $p$ region are oriented in opposite directions. When holes are injected from the $p^+$ region into the $p$ region, the quasineutrality of the latter sets the electron charge supplied from the external chain. Therefore, the electron charge fails to compensate for the entire charge of holes at the interface between the SCR and quasineutral $p$ region. The uncompensated hole charge at the interface is common for the SCR and quasineutral $p$ region. Thus, the electric fields of the SCR, $E(L)$, and the quasineutral $p$ region, $E(L + 0)$, are nonzero and $E(L) = -E(L + 0)$; i.e.,

$$\left( \frac{d\phi(x)}{dx} \right)_L = \left( \frac{d\phi(x)}{dx} \right)_{L+0}.$$  

In the case of a reverse-biased $p^+–p$ junction, the electric fields of the SCR, $E(L)$, and the quasineutral $p$ region, $E(L + 0)$, have the same direction, and $E(L) = E(L + 0)$; i.e.,

$$\left( \frac{d\phi(x)}{dx} \right)_L = \left( \frac{d\phi(x)}{dx} \right)_{L+0}.$$