

# Reversed Electron-Hole Pair Transport in SOI Structure

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## Abstract

A calculation of electron-hole pair drift velocity in silicon is represented. It was shown that the reversed pair drift must take place in  $n$ -silicon. The silicon-on-insulator structure was used for the reversed drift observation.

**Keywords** : silicon / SOI structure / electron-hole pair / electron and hole field heating / ambipolar drift / drift velocity / reversed drift

## 1. Introduction

In  $n$ -type semiconductors electron-hole pairs usually drift along the electrical field. However the electron and hole field heating can reverse the drift direction [1]. This non-obvious phenomenon is named reversed drift. Up to now it was observed only in germanium [1] and indium antimonide [2]. In this paper we present the calculation of drift velocity and observation of the reversed drift in silicon. We used the silicon-on-insulator (SOI) structures. Their properties ensured the simplicity of our experiment.

## 2. Theory

Let us consider the current flowing through a semiconductor containing the electron-hole plasma. In this semiconductor the electron and hole concentrations are  $n = n_0 + \Delta n$ ,  $p = p_0 + \Delta p$ , where  $n_0, p_0$  and  $\Delta n, \Delta p$  ( $\Delta n = \Delta p$ ) are their equilibrium concentrations and deviations from them, respectively.

The electron and hole conservation equations have the form

$$\frac{\partial \Delta n}{\partial t} = (g_n - r_n) + \frac{1}{e} \frac{\partial j_n}{\partial x}, \quad \frac{\partial \Delta p}{\partial t} = (g_p - r_p) - \frac{1}{e} \frac{\partial j_p}{\partial x}, \quad (1)$$

where  $g_{n,p}$ ,  $r_{n,p}$  ( $g_n - r_n = g_p - r_p$ ) are the generation and recombination rates for electrons and holes, respectively,  $j_{n,p}$  are their current densities,  $t$  is the time, and  $e$  is the electron charge. The electron and hole current densities can be written as follows

$$j_n = ev_n(E)n + eD_n \frac{\partial \Delta n}{\partial x}, \quad j_p = ev_p(E)p - eD_p \frac{\partial \Delta p}{\partial x}, \quad (2)$$

where  $v_{n,p}$  are the electron and hole drift velocities,  $D_{n,p}$  are their diffusion coefficients,  $E$  is the field strength. Substituting expressions (2) into equations (1), after apparent transformations [3] we get

$$\frac{\partial \Delta n}{\partial t} = (g_n - r_n) - V_{\text{amb}} \frac{\partial \Delta n}{\partial x} + D_{\text{amb}} \frac{\partial^2 \Delta n}{\partial x^2}, \quad (3)$$

where

$$V_{\text{amb}} = \frac{v_p (\partial v_n / \partial E) - v_n (\partial v_p / \partial E)(p/n)}{(\partial v_n / \partial E) + (\partial v_p / \partial E)(p/n)} \quad (4)$$

and  $D_{\text{amb}} = \frac{D_n D_p (n+p)}{D_n n + D_p p}$  are the ambipolar drift velocity and diffusion coefficient, respectively. In equation

(3) we neglected the impact of the electron and hole field heating on diffusion.

According to [4], in silicon at 300 K we have

$$v_n = \frac{1.44 \cdot 10^3 E}{\left(1 + 5.46 \cdot 10^{-5} E^{1.11}\right)^{0.90}}, \quad v_p = \frac{4.65 \cdot 10^2 E}{\left(1 + 6.90 \cdot 10^{-6} E^{1.21}\right)^{0.82}}, \quad (5)$$

where  $v_n$  and  $v_p$  are measured in [ $\text{cm s}^{-1}$ ], and  $E$  in [ $\text{V cm}^{-1}$ ].

Using equations (4) and (5) we calculated velocity  $V_{\text{amb}}$ . Curves 1-4 in Fig.1 present the  $V_{\text{amb}}$  vs  $E$  relationships at different  $p/n$  ratios. In  $n$ -silicon ( $p/n < 1$ ) at field strength  $E < E_{\text{rev}}$  velocity  $V_{\text{amb}} > 0$  (curves 3,4), and the ordinary drift takes place. But at  $E > E_{\text{rev}}$  velocity  $V_{\text{amb}} < 0$ , and the reversed drift exists.

The reversed ambipolar drift can not be realized in  $p$ -silicon ( $p/n \geq 1$ ) (see curves 1 and 2 in Fig.1).

The  $p/n$  ratio rising leads to decreasing of  $E_{\text{rev}}$  (Fig.1, curve 5). At high carrier injection levels ( $p/n \rightarrow 1$ ) the ambipolar drift direction reverses in weak fields. This conclusion is in agreement with the analytical theory [5].

In weak fields the electron  $\mu_n$  and hole  $\mu_p$  mobilities vary only slightly with field variations (look at the linear initial sections of curves 6 and 7 in Fig.1). The experiments described below were conducted just under such conditions.

### 3. Experimental structure

The *Si*-film of the SOI structure investigated is shown in Fig.2. Its thickness  $d$  is 0.4  $\mu\text{m}$ . The buried oxide and substrate thicknesses are 1  $\mu\text{m}$  and 400  $\mu\text{m}$ , respectively. Donor concentration  $N_d$  and electron-hole pair diffusion length  $L_D$  are  $5 \times 10^{15} \text{ cm}^{-3}$  and 2  $\mu\text{m}$ , respectively. The narrow channel connects two wide parts of the film. Its length  $a$  and width  $b$  are 4  $\mu\text{m}$  and 2  $\mu\text{m}$ , respectively. Currents  $I_+$  and  $I_-$  flow through the  $p^+ - n$  and  $n^+ - n$  junctions of the corresponding wide parts of the film. They create the electron-hole pair reservoirs at the channel ends. Let us designate the pair concentrations in these reservoirs as  $p_+$  and  $p_-$ . The  $I$  current flows through the channel. It causes voltage drop  $U$  between the  $p^+ - n$  junction of  $p_+$  reservoir and  $n^+ - n$  junction of  $p_-$  reservoir.

At  $U/a \gg E_{\text{dif}} = kT/eL_D$  the pair drift prevails over diffusion. Under such conditions our structure design allows us to determine the drift type. In fact, the pairs drift into the channel from one of the reservoirs and increase the  $I$  current through the channel. They drift from the  $p_+$  reservoir into the channel under the ordinary drift. In this case the  $I_+$  current rise increases the  $I$  current due to the  $p_+$  concentration increasing. On the other hand, the pairs drift from the  $p_-$  reservoir into the channel under the reversed drift. Therefore, under the reversed drift the current  $I_-$  rise increases the  $I$  current due to the  $p_-$  concentration increasing.

#### 4. Experimental results and discussion

The  $I$  vs  $U$  relationships are shown in Fig.3 for several  $I_+$  and  $I_-$  values. These values are written above the corresponding curves. These relationships were the same for pulsed (pulse duration was 1  $\mu$ s) and stationary current measurements. This proves that channel heating is small. The small heating is ensured with the intensive heat flows into the SOI structure contacts and substrate.

We can see that the rise of the  $I_-$  current increases current  $I$  by more than two-fold (compare curves 1 and 3 (or 2 and 4)). According to Section 3, this indicates that the reversed drift does take place.

The  $I$  current rise due to the increasing of  $I_+$  current is small (compare curves 1 and 2 (or 3 and 4)). The decrease of  $p_+$  reservoir resistance owing to the  $I_+$  current rise explains the small increase of current  $I$  in this case.

Reversed drift increases the pair concentration in the channel only up till maximum value  $p_-$  determined by current  $I_-$ . Thereafter the channel current is

$$I = ebd \cdot [v_n(N_d + p_-) + v_p p_-] . \quad (6)$$

If the field strength is small, then  $v_{n,p} = \mu_{n,p}E$  (curves 6 and 7 in Fig.1), and  $I \propto U$  (curves 1-4 in Fig.3). The equation (6) allows to explain the breaks of lines 1 and 2 in Fig.3. These breaks are caused by both the  $p_-$  concentration decrease at  $I > I_-$  and the sublinear behaviour of the  $v_{n,p}$  vs  $E$  curves in high fields (curves 6 and 7 in Fig.1).

An attempt of the ordinary drift observation has failed. The condition

$$E_{\text{dif}} \ll U/a < E_{\text{rev}} \quad (7)$$

should be satisfied for the observation of ordinary drift. We used expression (6) at small values of field strength, and from the curves in Fig.3 we found that  $p/n = 0.97-0.99$  were realized in our experiments. According to curve 5 in Fig. 1 values  $E_{\text{rev}} = (390-130) \text{ V cm}^{-1}$  correspond to these  $p/n$  values. The  $E_{\text{dif}}$  field strength is  $125 \text{ V cm}^{-1}$ . This value and  $E_{\text{rev}}$  values are close, and condition (7) is not satisfied. Therefore we could not observe the ordinary drift.

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## FIGURE CAPTIONS

Fig.1. Curves 1-4 – the ambipolar drift velocity  $V_{\text{amb}}$  vs electric field  $E$  curves for the different  $p/n$  ratios. Curve 5 - the  $E_{\text{rev}}$  field of drift reversing vs  $p/n$ . Curve 6,7 – the electron  $v_n$  and hole  $v_p$  drift velocities vs  $E$ .

Fig.2. Experimental SOI structure.

Fig.3.  $I-U$  curves for the different  $I_+$  and  $I_-$  current ratio.

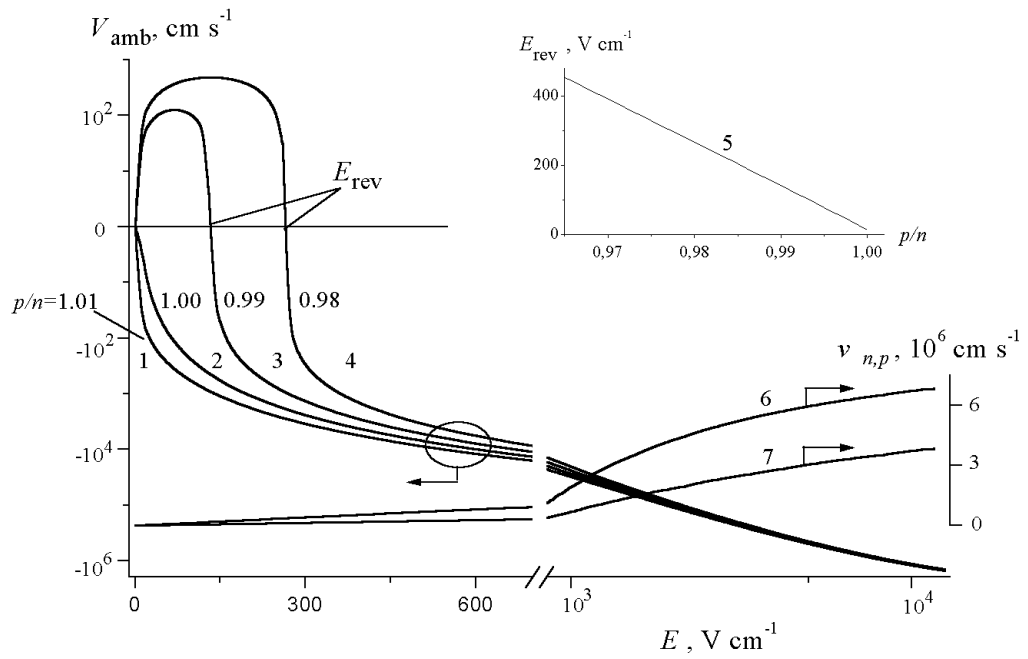


Fig.1

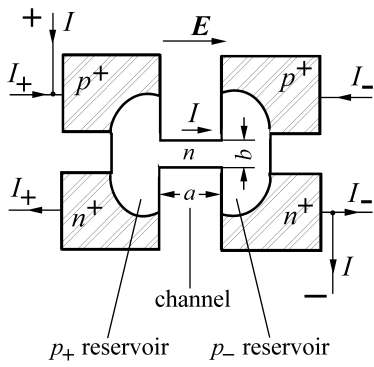


Fig.2

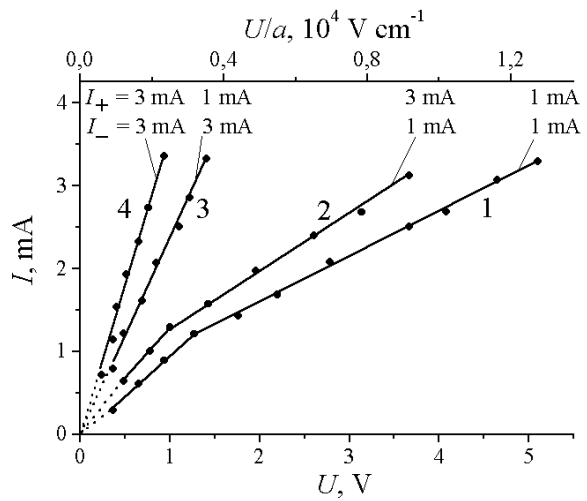


Fig.3