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ON THE RECOMBINATION IN THE QUASI-NEUTRAL BASE OF POLYSILICON EMITTER TRANSISTORS WITH INTERFACIAL OXIDES

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1. INTRODUCTION

The current gain of polysilicon emitter transistors can be dramatically increased by introducing an interfacial oxide between the polysilicon and monosilicon parts of the emitter. Although the physical mechanism is not fully understood, this oxide suppresses the injection from the base into the emitter for both *npn* and *pnp* devices[1,2].

Ashburn *et al.* reported that the base current in *npn* polysilicon emitter bipolar devices with a deliberately grown interfacial oxide is suppressed to such an extent that electron recombination in the quasi-neutral base becomes an important base current component[3]. We have detected base recombination indeed. The strong dependence of the base current on the collector–base voltage reported, however, may be due to impact ionization in the collector–base depletion region.

2. DEVICE FABRICATION

The *npn* and *pnp* transistors used in this study were fabricated on separate wafers. The collector was formed by means of high-energy ion implantation. The implantation species for the *npn* transistors was *P* with an energy of 1.5 MeV to a dose of 1×10^{13} or $2 \times 10^{13}\,\mathrm{cm^{-2}}$. For the *pnp* device, *B* was used with an energy of 1 MeV to a dose of $3 \times 10^{13}\,\mathrm{cm^{-2}}$. The interfacial oxide was made by immersing the wafers in hot 60% nitric acid for 10 min. Subsequently, a 300 nm thick undoped polysilicon layer was deposited. The polysilicon was implanted after deposition with arsenic (100 keV, $4 \times 10^{15}\,\mathrm{cm^{-2}}$) or *B* (40 keV, $2.5 \times 10^{15}\,\mathrm{cm^{-2}}$).

3. RESULTS

In Fig. 1, the Gummel plot of the *npn* device with the higher collector dose is shown for three different collector–base voltages, 0, 3.75 and 4.25 V. The emitter area of this device is $4 \times (25 \times 25)\,\mu\mathrm{m}^2$. The common-emitter current gain is about 2000 at moderate V_{be} (0.6–0.7 V). Corresponding devices without a deliberately grown interfacial oxide had typical current gains of about 70. Thus the interfacial oxide strongly reduces the base current. The collector current is ideal over 7 decades. It varies only a little bit with increasing collector–base voltage V_{cb}. Therefore, it can be concluded that minor extension of the collector–base depletion region into the base occurs for higher V_{cb}. The base current, however, is a strong function of V_{cb}. The base current at a V_{cb} of 3.75 V is considerably lower than that at a zero-biased collector–base. At $V_{cb} = 4.25$ V, the base current even temporarily changes its sign. This is attributed to impact ionization in the collector–base space charge region[4–6]. At $V_{cb} = 4.25$ V, the carrier generation in the collector–base depletion region caused by impact ionization can be so heavy that the direction of the base current is opposite. On the other hand, its contribution to the collector current is small.

The field-dependent electron ionization rate may be written as[6,7]:

$$\alpha_n(x) = \alpha_n^0 \exp\left[-\frac{E_c}{E(x)}\right], \tag{1}$$

where $E(x)$ is the local electrical field. α_n^0 is the avalanche coefficient and E_c the critical electrical field. In simulations presented later on, the following values for α_n^0 and E_c are used: $\alpha_n^0 = 7.0 \times 10^5\,\mathrm{cm^{-1}}$ and $E_c = 1.2 \times 10^6\,\mathrm{V\,cm^{-1}}$.

The extra collector current generated through impact ionization is:

$$I_g = \int_a^b I_c \alpha_n(x)\,dx, \tag{2}$$

where a and b are the boundaries of the collector–base depletion region. In the area of interest, I_c is much larger than I_g. Therefore, I_c is assumed to be constant and I_g can be written approximately as:

$$I_g = \alpha_n^0 I_c \int_a^b \exp\left[-\frac{E_c}{E(x)}\right] dx. \tag{3}$$

From equation (3) an exponential dependence of I_g on the collector–base voltage V_{cb} may be predicted. The impact of I_g on the collector current is of minor importance, but it can affect the base current. The importance of I_g with respect to the base current can be expressed by the following equation:

$$\Delta_{b.imp} = \frac{I_g}{I_{b0}}, \tag{4}$$

where I_{b0} is the base current at the zero-biased collector–base junction. When the collector–base voltage is increased, the depletion layer will further extend into the base and the quasi-neutral base width will decrease. Therefore the recombination of electrons in the quasi-neutral base becomes less with increasing V_{cb}. The deviation of the base current, due to a reduced base recombination, is described by:

$$\Delta_{b.rec} = \frac{I_{b0} - I_b(V_{cb})}{I_{b0}}. \tag{5}$$

The total deviation of the base current at a certain V_{cb} follows from the summation of equations (4) and (5). It can be written as:

$$\Delta_{b.tot} = \frac{I_{b0} - I_b(V_{cb}) + I_g}{I_{b0}}. \tag{6}$$

Simulations were carried out to investigate the components $\Delta_{b.imp}$, $\Delta_{b.rec}$ and $\Delta_{b.tot}$. Since our device simulator does not account for any interfacial oxide, the polysilicon interface was modelled by means of an effective recombination velocity S_{pi} of $1 \times 10^3\,\mathrm{cm^{-1}}$. This value corresponds very well with typical values reported elsewhere[8]. The electron recombination in the quasi-neutral base depends on the electron lifetime. In the doping region of interest, the

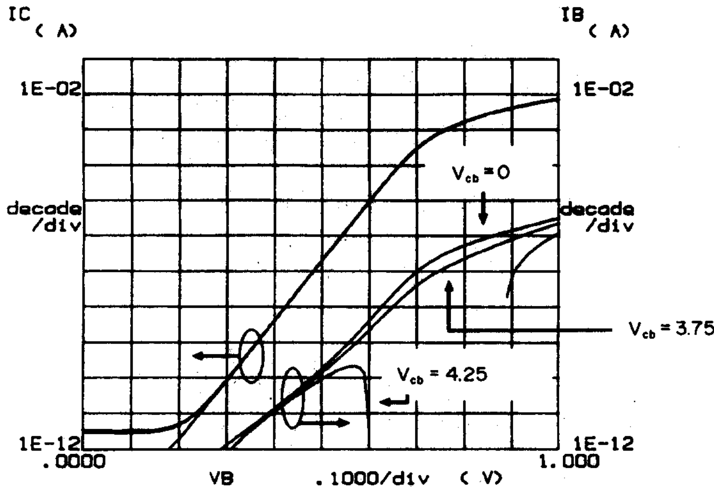

Fig. 1. A Gummel plot of the *npn* device with the higher collector dose. The collector current hardly varies with increasing V_{cb}. On the other hand, the base current is a strong function of V_{cb} due to impact ionization in the collector–base depletion region.

electron lifetime is mainly determined by SRH-recombination and can be written as:

$$\frac{1}{\tau_n} = \frac{1}{\tau_o} + \frac{1}{\tau_{SRH}} = \frac{1}{\tau_o} + C_{SRH} N_A \quad (7)$$

In our simulations τ_o and C_{SRH} are 1 μs and 1×10^{-11} cm^3 s^{-1}, respectively.

For the *npn* transistor with the higher collector concentration, the simulation results of $\Delta_{b.imp}$, $\Delta_{b.rec}$ and $\Delta_{b.tot}$ are plotted in Fig. 2. Agreement between the simulated and measured values is good. At low V_{cb}, the base current deviation can be attributed to a reduced electron recombination in the quasi-neutral base. The simulations point out that 20% of the base current originates from electron recombination in the quasi-neutral base. At V_{cb} higher than 2 V, the impact ionization gives rise to a pronounced increase of the base current deviation. It can be observed from the figure that the impact ionization exhibits an exponential behaviour indeed.

In Fig. 3, the relative base current deviation is illustrated including the other *npn* and *pnp* devices. The decrease of the base current, caused by impact ionization in the collector–base depletion region, is already significant at low V_{cb} for the *npn* devices. Lowering the collector concentration at the collector–base junction, by means of a reduction of the *P* implantation dose, results in lower ionization rates at a given V_{cb}. For V_{cb} voltages less than 2 V, the base current of the *npn* devices varies only little with an increasing V_{cb}. As stated earlier, this is due to electron recombination in the quasi-neutral base. Compared to the decrease of the base current, as reported by Ashburn *et al.*[3], the reduction due to base recombination is small in our devices. However, the modulation of the quasi-neutral base region for our devices is minimal.

The *pnp* device does not exhibit impact ionization, because the ionization rate of holes is about three orders of magnitude lower than that of electrons at a fixed electrical field[7]. As a consequence, the base current of *pnp* devices is only affected by impact ionization at much higher $|V_{cb}|$. The small decrease of the base current, found for the *pnp* device, is caused by a reduced hole recombination in the quasi-neutral base region.

4. CONCLUSIONS

The importance of recombination in the quasi-neutral base has been measured on *npn* and *pnp* polysilicon emitter transistors with a deliberately grown interfacial oxide. In the case of *pnp* devices, minor deviation of the base current

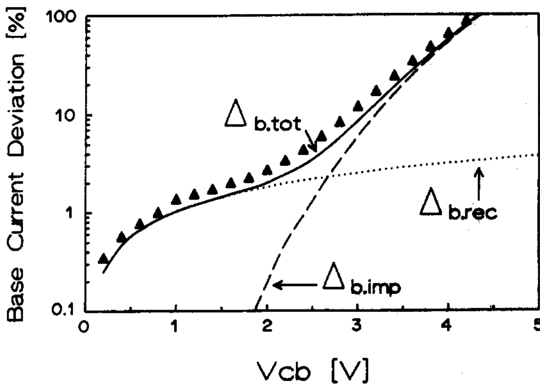

Fig. 2. The simulated and measured base current deviation as a function of the collector–base voltage for the *npn* device with the high collector dose. The triangles represent the measured data

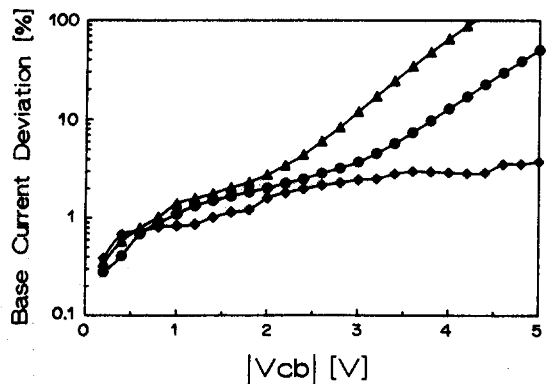

Fig. 3. The measured base current deviation as a function of the absolute collector–base voltage for the *npn* transistor with the high collector dose (▲), the low collector dose (●) and the *pnp* transistor (◆).

could be detected. Two regions can be distinguished for the *npn* devices: In the first region (low V_{cb}), a small deviation of the base current is caused by reduced electron recombination in the quasi-neutral base. In the second region (higher V_{cb}), an exponential dependence is found, which is due to impact ionization in the collector–base depletion region. It can be concluded that a deliberately grown interfacial oxide considerably suppresses the base current. As a result, carrier recombination in the quasi-neutral base may become important. Simulations reveal that 20% of the base current can arise from base recombination. The influence of impact ionization in the collector–base space charge region, however, becomes important at lower reverse collector–base bias.

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