Phosphorus-Implanted Polysilicon Emitters with High Emitter Efficiency

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Phosphorus-doped polysilicon emitters have been fabricated with a low emitter series resistance and an emitter efficiency that is 4-5 times higher than that of arsenic-doped polysilicon emitters. These emitters have been realized using conventional ion implantation and rapid thermal annealing. We present a model, which explains the magnitude as well as the temperature dependence of the hole-recombination current in these emitters. This model predicts, in agreement with our experiments, that the emitter efficiency increases for shallower emitters. We also elucidate the difference between arsenic and phosphorus-doped polysilicon emitters.

Introduction

Recently, Kondo et al. [1] and Nanba et al. [2] have shown that, with in-situ phosphorus-doped amorphous silicon, very shallow emitters can be made with a very high emitter efficiency and a low emitter series resistance. Here, we show that a similar result can be achieved, using standard polysilicon deposition, phosphorus implantation and RTA annealing. We present a model, which explains the magnitude, as well as the temperature dependence, of the hole-recombination current in these emitters. Furthermore, we show that the difference between arsenic and phosphorus-doped polysilicon emitters can be explained in terms of perforation of the interfacial barrier between mono- and polysilicon.

Experiments and Results

In a non-selfaligned transistor structure, the base was introduced by a 10 keV B implantation in monosilicon, with doses of 1.2, 2.4 and $3.6 \times 10^{13} \text{cm}^{-2}$, and annealed for 20 minutes at 900 °C. For emitter formation, a 200 nm-thick CVD polysilicon layer was deposited after HF dipping and implanted with P, using a dose of $1.0 \times 10^{16} \text{cm}^{-2}$. RTA annealing, at temperatures between 900 and 975 °C, during 7 seconds, was used for emitter outdiffusion into the monosilicon. As a reference, one of the wafers was not implanted with P but with $1.0 \times 10^{16} \text{cm}^{-2}$ As. This wafer was RTA annealed 7 seconds at 1100 °C.

Figure 1 shows very shallow P profiles obtained by SIMS, displaying junction depths of 58 nm and 70 nm for transistors annealed at 900 and 975 °C, respectively. The effective emitter Gummel number $G_E$ of our transistors, shown in fig. 2, ranges between 54 and 82$\times 10^{12}$ s$^{-1}$ cm$^{-1}$. $G_E$ increases for decreasing annealing temperature and for increasing base doping. Both trends correspond to a higher $G_E$ for a shallower emitter-base junction. $G_E$ of the As-doped emitter is $18 \times 10^{13}$ s$^{-1}$ cm$^{-1}$. The 4-5 times higher $G_E$ for the P-doped emitters is also reflected in the Gummel plot of fig. 3, which shows ideal base-current characteristics. The emitter resistance $R_E$ did not show a dependence on the annealing temperature. $R_E = 33(\pm 5) \Omega \mu \text{m}^2$, for both the P and As-doped emitters, as obtained from measurements on transistors with emitter areas
of 4 and 120 \( \mu \text{m}^2 \).

The high \( G_E \)—combined with low \( R_E \)—values indicate the presence of a very effective hole barrier at the poly-mono interface, that does not act simultaneously as an electron barrier. The effective surface recombination velocity \( S_{\text{eff}} \) at the poly-mono interface was determined from a comparison of measured base currents with 1D-device simulations, using the doping profile obtained by SIMS [3] (see fig 4). For the As-doped emitters \( S_{\text{eff}} \) is quite high and only weakly dependent on temperature. For the P-doped emitters, however, \( S_{\text{eff}} \) shows a strong dependence on temperature and is much lower. These low values of \( S_{\text{eff}} \) indicate that, even for these very shallow emitters, recombination in the monosilicon is the main origin of the base current. This explains why the shallower P-doped emitters have the higher \( G_E \).

**Interpretation and Discussion**

Assuming that the hole-diffusion length in the polysilicon is much smaller than the poly thickness, \( S_{\text{eff}} \) is given by

\[
S_{\text{eff}} = \frac{v_d v_{tr}}{v_d + v_{tr}}
\]

(1)

Here, \( v_d \) is the minority diffusion velocity in the polysilicon and \( v_{tr} \) is the velocity at which holes cross the interface from mono to poly and from poly to mono. For the P-doped emitter \( S_{\text{eff}} \) exhibits over more than one decade an exponential dependence on the inverse temperature. This suggests that thermionic emission of holes with mass \( m \) over a potential barrier with height \( \Phi_B \) is the predominant transport mechanism and, hence,

\[
v_{tr} = \sqrt{\frac{kT}{2\pi m}} \exp\left(-\frac{\Phi_B}{kT}\right) = v_{tr,0} \exp\left(-\frac{\Phi_B}{kT}\right)
\]

(2)

Fitting eqs. 1,2 to the values of \( S_{\text{eff}} \) (solid lines in fig. 4) yields for the P-doped emitter: \( \Phi_B = 220 \text{ mV}, \ v_d = 4 \times 10^6 \text{ cm.s}^{-1} \) and \( v_{tr,0} = 3 \times 10^7 \text{ cm.s}^{-1} \), while for the As-doped emitter \( \Phi_B = 75 \text{ mV}, \ v_d = 2 \times 10^6 \text{ cm.s}^{-1} \) and \( v_{tr,0} = 3 \times 10^6 \text{ cm.s}^{-1} \) is found. The values of \( v_{tr,0} \) and \( v_d \) found for the P-doped emitter are reasonable, but especially the large difference in the values of \( v_{tr,0} \) found for P and As-doped emitters (extrapolation of dashed lines to \( T^{-1} = 0 \)) seems unphysical. Inspection of the poly-mono interface of both emitters (see HRTEM fig. 5) points, however, to
Fig. 5: HRTEM of poly-mono interface of As (a) and P-doped (b) polyemitter.

A plausible explanation: for the P-doped emitter a continuous amorphous layer is visible between the poly- and monosilicon, while for the As-doped emitter the interface has been reconstructed and, on the recrystallized areas, gaps are visible in the amorphous layer.

To investigate the effects of such perforated barrier, we developed an analytical method to calculate $S_{eff}$ for a 2D homogeneously doped emitter. This rather simple method allows extensive variations of parameters and reproduces the results of 2D device simulations [4, 5]. In fig. 6 the results are shown found for $S_{eff}$ of a 1 μm-wide emitter, as a function of the transparency (i.e., fraction of the surface where no barrier exists) and the number of gaps. In this calculation the transport across the barrier from the poly to the mono was neglected, leading to a $S_{eff}$ not limited by $v_d$ at high $T$. This procedure is justified by the observation that for a perforated barrier diffusion through the gaps is the dominant transport mechanism and the details of the intact interfacial regions are of secondary importance [4]. From fig. 6 we see that a relatively low transparency divided over only a few gaps, is indeed sufficient to explain the difference between the P and As-doped emitters.

Conclusions

In our phosphorus-implanted polysilicon emitters a hole barrier at the poly-mono interface suppresses hole injection into the polysilicon. This results in a hole current which, at room temperature, is dominated by recombination in monosilicon. Consequently the shallower phosphorus-doped emitters have higher effective emitter Gummel numbers.

The higher value and the weaker temperature dependence of the base current in our arsenic-doped emitters is explained by perforation of the interfacial barrier.

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References

[3] G. Streutker et al., to be presented at BCTM’92.