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Evidence of low injection efficiency for implanted p-emitters in bipolar 4H-SiC high-voltage diodes

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ABSTRACT

In this study, the influence of the emitter efficiency on the forward current–voltage characteristics, especially the conductivity modulation of bipolar SiC-diodes was analyzed. It was determined that the emitter efficiency of p-emitters formed by ion implantation is significantly lower compared to p-emitters formed by epitaxy. In contrast to comparable studies, experimental approach was arranged that the influence of the quality of the drift-layer or the thickness of the emitter on the conductivity modulation could be excluded for the fabricated bipolar SiC-diodes of this work. Thus, it can be established that the lower emitter injection efficiency is mainly caused by the reduced electron lifetime in p-emitters formed by ion implantation. Therefore, a significant enhancement of the electron lifetime in implanted p-emitters is mandatory for e.g. SiC-MPS-diodes where the functionality of the devices depends significantly on the injection efficiency.

1. Introduction

In recent years, the surge current capability of unipolar Schottky (JBS) diodes based on the wide bandgap semiconductor SiC could be improved significantly by the introduction of a merged pn-Schottky structure (MPS-diode) [1–3]. In contrast to traditional Schottky diodes, MPS-diodes consist of p-emitters below or next to the Schottky interface. Recently, Niwa et al. [2] demonstrated that MPS-diodes with p-emitters formed by epitaxy are endued with a significantly lower differential on-resistance compared to MPS-diodes with p-emitters formed by ion implantation. This was attributed to defects generated during ion implantation within the p-emitter regions and extending in the drift layer, too [2]. A similar assumption was pointed out by Kimoto et al. [3]. However, the manufacturing of MPS-diodes with ion implanted p-emitters leads to both a significantly lower process effort and a straightforward device architecture. In case of a surge current, the p-emitters inject holes into the drift layer. The conductivity of the drift layer under the metal contact increases strongly for the case of high level injection, i.e. the density of the injected carriers is significantly higher than the doping of the drift layer. This behavior of bipolar semiconductor devices is well known as conductivity modulation and leads to a reduction of the differential on-resistance of bipolar high-voltage diodes in general and MPS-diodes in case of a surge current [4]. The surge current capability is required for freewheeling diodes and short circuit protection, e.g. in converters for wind turbines [5]. In order to increase the surge current capability further improvements of the conductivity modulation leading to a lower differential on-resistance are mandatory. A more effective conductivity modulation can be achieved by a higher ambipolar lifetime and mobility of the charges within the drift layer [3]. For that, the defect density within the drift layer has to be reduced [6]. It could be demonstrated by several groups, that beside the ambipolar carrier lifetime in the drift-layer, the injection efficiency of the p-emitter has to be taken into account, too, in order to decrease the static conduction losses. It was assumed that defects within the p-emitter and the drift-layer reduce the diffusion length of electrons in the p-emitters and the diffusion length of holes in the drift-layer, respectively. According to the theory of bipolar pn-diodes, for a given forward current density, the concentration of holes injected into the drift-layer and the conductivity modulation is reduced. Kimoto et al. explained the higher differential on-resistance of 11 kV MPS-diodes with ion implanted emitter compared to MPS-diodes with epitaxially grown emitter by this lower emitter injection efficiency [3]. A similar assumption was pointed out earlier by Lendenmann et al. for 4.5 kV 4H-SiC pn-diodes [7]. In contradiction to these studies, several examinations attribute the higher differential on-resistance of pn-diodes with implanted p-emitters to the lower thickness of the p-emitters [8–12] and to the recombination at the ohmic contact [13].

The injection efficiency of implanted p-emitters is under investigation for several years, but there is no consistent physical explanation by now. The main reason for this is the limited comparability of the

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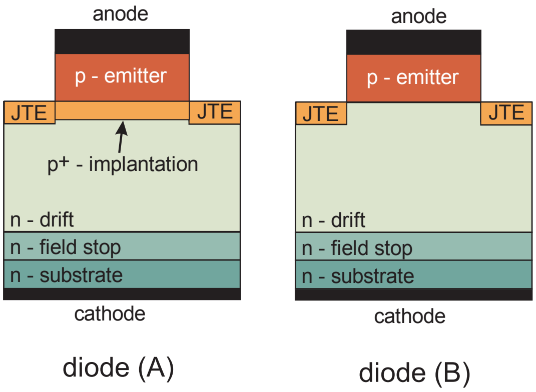

Fig. 1. Schematic cross section of the implemented pn-diodes, fabricated on the same substrate: diode (A) with implanted p^+-layer below epitaxial p^+-emitter, and diode (B) without implanted p^+-layer.

experimental results.

For this purpose, a concise experimental approach is demonstrated in this work. Based on the experimental results, it will be figured out that the reduced injection efficiency of p-emitters formed by ion implantation has to be attributed to a reduced diffusion length of electrons inside the p-emitter. Additional influences like the thickness of implanted p-emitters, the recombination at the ohmic contact, and the different quality of the drift layer material, can be excluded.

2. Experimental procedure

As mentioned before, physical parameters influencing the injection efficiency of a p-emitter formed by ion implantation will be discussed in this study especially for a possible improvement of bipolar high-voltage diodes. For this, the forward conduction properties of specific pn-diodes designed as test devices with an implanted p-emitter were analyzed and compared to the forward conduction properties of pn-diodes with a p-emitter formed by epitaxy. In Fig. 1 the schematic cross sections of the pn-diodes with implanted layer (A) and epitaxial grown p-emitter (B) analyzed in this study are shown.

To ensure a comparable quality of the drift layer, both pn-diode (A) and (B) were fabricated on the same n-doped 4H-SiC substrate on which the field stop and drift layer were grown by epitaxy. The thickness of the field stop-layer d_{FS} was 2 µm and the doping concentration $N_{D,FS}$ of $2 \times 10^{17}\,\mathrm{cm}^{-3}$, whereby the drift-layer was endued with a thickness $\mathrm{d_D}$ of 50 µm and a nominal doping-concentration $N_{D,D}$ of $1 \times 10^{15}\,\mathrm{cm}^{-3}$. The doping concentration within the drift layer was determined by C-V-measurements leading to a value of $N_{D,D}$ of $(3 \pm 0.7) \times 10^{15}\,\mathrm{cm}^{-3}$.

As known from literature, the influence of the thickness of the p-emitter on the forward conduction characteristics is negligible for thicknesses of the p-emitter higher than the diffusion length of electrons in the p-emitter [14]. Following this assumption, for both kinds of pn-diodes a highly doped ($N_A = 1 \times 10^{19}\,\mathrm{cm}^{-3}$) p-emitter with a thickness of 5 µm was grown by epitaxy. In case of pn-diode (A) an additional p^+-emitter was previously formed by ion implantation under the p-epitaxy. The implantation energies were 35 keV, 100 keV, 200 keV, and 400 keV, respectively, with doses of $1 \times 10^{14}\,\mathrm{cm}^{-2}$, $1 \times 10^{14}\,\mathrm{cm}^{-2}$, $2 \times 10^{14}\,\mathrm{cm}^{-2}$, and $3 \times 10^{14}\,\mathrm{cm}^{-2}$, respectively. The resulting p^+-emitter has a box-profile with a thickness of approximately 500 nm and a doping-concentration of $1 \times 10^{19}\,\mathrm{cm}^{-3}$. Subsequently, the epitaxially grown p-emitter was structured by dry etching, a junction termination extension was formed by ion implantation and a subsequent annealing at 1700 °C for 30 min using a carbon capping layer was conducted. According to the literature [15–17], this annealing sequence leads to a high degree of electrical activation of dopants. However, a small fraction of electrically inactive dopants as well as compensation effects due to defects generated by the ion implantation process may reduce the electrically active acceptor concentration in the implanted p-emitter. The amount of these effects is roughly estimated and discussed in the next section. Finally, the contact metallization was deposited, whereby the backside ohmic contact was realized by alloying a 100 nm thick Ni layer. Before depositing the 4 µm thick front side Ti/Al metallization stack, a front side ohmic contact was formed by alloying a 100 nm thick NiAl layer. The active device area was 400 × 400 µm.

3. Results and discussion

The injection efficiency γ of the p-emitter strongly influences the forward conduction characteristics of bipolar SiC diodes. Thereby, the forward conduction properties are determined by the forward voltage drop V_F (J_F). According to Eq. (1)

$$V_F(J_F) = V_{PN} + r_D J_F \tag{1}$$

the forward voltage drop is a function of the built-in voltage V_{PN} of the pn-junction between the p-emitter and the drift layer, the forward current density J_F, and the differential on-resistance r_D.

For high forward current densities, the differential on-resistance results from the thickness of the drift layer d_D, the ambipolar mobility $(\mu_n + \mu_p)$, and the ambipolar lifetime τ_A. Due to the short ambipolar lifetime and the comparably low injection efficiency in SiC, the electron mobility μ_n and the electron concentration n resulting from the doping concentration $N_{D,D}$ is not negligible. Hence, the equation for calculating the differential resistance well known from bipolar Si diodes [4] with q being the elementary charge has to be adjusted for bipolar SiC diodes to

$$r_D = \frac{d_D}{(\mu_n + \mu_p)\,\frac{J_F\,\gamma\,\tau_A}{d_D} + q\,\mu_n\,n}. \tag{2}$$

For a given thickness and doping concentration of the drift layer the influence of the injection efficiency of the p-emitter and the ambipolar lifetime, respectively, can be determined by evaluating the differential on-resistance. However, compensation effects and the possibility of an incomplete electrical activation of acceptors in case of the implanted emitter have to be considered, too. As mentioned and described in the past by several groups [15–17], the fraction of the electrically active and non-compensated dopants is supposed to be higher than 50% of the implanted aluminum dose for the applied implantation and annealing parameters. In order to analyze the influence of lower effective acceptor concentrations in case of the implanted p-emitter (diode (A)) compared to the epitaxially grown p-emitter without subjacent p-implantation (diode (B)) a worst case estimation lead to a lowering of the emitter injection efficiency for such devices of less than 10%. Thus, a small difference in the characteristic of both devices may be ascribed to these phenomena.

The current density-voltage characteristic of bipolar SiC pn-diodes with p-emitters, formed by ion implantation (pn-diode (A)) and by epitaxy (pn-diode (B)) were measured and analyzed. In Fig. 2 the measured forward current density in dependence of the applied voltage and temperature of the pn-diodes (A) and (B) are shown in linear scale. In this figure, an additional line represents the power loss of $300\,\mathrm{W\,cm}^{-2}$, which is introduced as a typical package thermal limit [18]. By this, the maximum current density is limited by the forward voltage drop regarding the thermal limit.

Furthermore, Fig. 3 outlines the extracted forward voltage drop of the pn-diodes (mean value and standard deviation) for different forward current densities (exemplarily chosen: $100\,\mathrm{A\,cm}^{-2}$ and $500\,\mathrm{A\,cm}^{-2}$) in dependence on the temperature. Obviously, the forward voltage drop of the pn-diodes (B) is significantly lower than the forward voltage drop of the pn-diodes (A) for a given current density, at least for temperatures below 175 °C. This is underlined by the small standard deviation of the forward voltage drop between all analyzed diodes (represented by error-bars in Fig. 3).

The differential on-resistance results from the slope of the J-V-