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High-temperature high-voltage *p–i–n* diodes based on low doped heteroepitaxial layers AlGaAs and AlGaAsSb

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Abstract. The article investigates the temperature dependences of the current–voltage characteristics and reverse recovery of high-voltage $Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As_{1-y}Sb_y$ *p–i–n* diodes manufactured by liquid-phase epitaxy when heated to 350 °C. It was found that with an increase in the Al content in the base layers, the operating temperatures of the diodes increase from 250 °C at $x = 0$ to 350 °C at $x \sim 0.45$, while the forward voltage drops of the diodes also increase. It is shown that the use of small Sb additions in AlGaAs layers reduces the reverse recovery times of diodes by almost an order of magnitude, from 40–80 ns to 5–8 ns.

Keywords: AlGaAsSb, heterostructure, high-voltage p^0-i-n^0 junction, diode, liquid-phase epitaxy, lattice mismatch, reverse recovery of diodes

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Материалы конференции
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Высокотемпературные высоковольтные *p–i–n* диоды на основе слаболегированных гетероэпитаксиальных слоев AlGaAs и AlGaAsSb

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Аннотация. В работе исследованы температурные зависимости вольт-амперных характеристик и обратного восстановления высоковольтных $Al_xGa_{1-x}As$ и $Al_xGa_{1-x}As_{1-y}Sb_y$ *p–i–n* диодов, изготовленных методом жидко-фазной эпитаксии, при нагреве до 350 °C. Выяснено, что с увеличением доли Al в базовых слоях рабочие температуры диодов повышаются от 250 °C при $x = 0$ до 350 °C при $x \sim 0.45$, при этом увеличиваются прямые падения напряжения диодов. Показано, что применение малых добавок Sb в слои AlGaAs позволяет уменьшить времена обратного восстановления диодов почти на порядок, с 40–80 нс до 5–8 нс.

Ключевые слова: AlGaAsSb, гетероструктура, высоковольтный $p^0–i–n^0$-переход, диод, жидко-фазная эпитаксия, рассогласование по параметру решетки, обратное восстановление диодов

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Introduction

Modern power electronics and pulse technique are developing to create high-speed devices capable of operating at increased frequencies and temperatures. Using wide-band AlGaAs solid solutions allows to increase operating temperatures above 300 °C [1]. Introducing small amounts of Sb or In additives into GaAs or AlGaAs-based layers can increase device speed and reduce electrical losses during switching by controlling the formation of structural defects in heterostructures with a specific lattice parameter mismatch [2].

Materials and Methods

Epitaxial growth of high-voltage low doped gradual AlGaAs and AlGaAsSb $p^0–i–n^0$ junctions was carried out using a modified liquid-phase epitaxy (LPE) method in a piston-type graphite container. The growing processes were carried out on p^+-GaAs substrates with an orientation of (100), doped with zinc up to $5 \cdot 10^{18}$ cm^{-3}, from a confined solution-melt Al–Ga–As or Al–Ga–As–Sb, at temperatures ranging from 900–850 °C to 750–700 °C. This was followed by the growth of a tellurium-doped n^+-GaAs emitter layer with a doping concentration of $2 \cdot 10^{18}$ cm^{-3}. The technique for obtaining gradual $Al_xGa_{1-x}As$ $p^0–i–n^0$ junctions from a single solution melt due to autodoping with background impurities was described earlier in [1, 3]. Samples of diodes (chips) had the form of mesa structures, which were obtained by chemical etching of active layers down to the substrate. A multilayer AgMn–Ni–Au contact was applied to the p^+-GaAs substrate, and AuGe–Ni–Au was applied to the n^+-GaAs emitter.

Measurements of the device characteristics were conducted in continuous and pulsed modes at temperatures ranging from 20 °C to 350 °C. The maximum test temperature for the diodes was limited by the capabilities of the measurement equipment utilized.

The temperature dependence of the effective minority carrier lifetime (τ_{eff}) using the reverse recovery time of $p^+–p^0–i–n^0–n^+$ diodes [4, 5] were investigated. The reverse recovery method involves applying rectangular pulses of forward (I_f) and reverse current (I_r) to the diode with specific signal amplitudes and durations. The reverse recovery time of a diode, which is the time it takes for the diode to switch from the conducting state to the blocking state, is composed of two phases: the duration of high reverse conductivity t_1 (during which the magnitude of the reverse current remains constant) and the decay of the reverse current t_2. The total recovery time $t_r = t_1 + t_2$ depends on the effective lifetime of minority carriers, and, consequently, on the density of defects and impurities with deep levels and their capture cross sections. By maintaining a constant ratio of forward and reverse current pulse amplitudes ($I_f/I_r \sim 5–6$), it can be approximated that $t_1 \approx \tau_{eff}$ [5].

Results and Discussion

The current–voltage characteristics at different temperatures and reverse recovery time of $p^+–p^0–i–n^0–n^+$ diodes based on high-voltage low doped layers of GaAs, $GaAs_{1-y}Sb_y$, $Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As_{1-y}Sb_y$ with different compositions were obtained. Fig. 1 shows the temperature dependence of the forward current–voltage characteristic in the static mode of *p–i–n* diodes based on a low doped $GaAs_{1-y}Sb_y$ layer (with y ~ 0.02) and a wider bandgap $Al_xGa_{1-x}As$ layer (with a maximum AlAs content in the layer x up to 0.45). It was found that increasing the Al content in the layers (and consequently the bandgap) leads to an increase in the operating temperatures of the diodes from approximately 250 °C at $x = 0$ to around 350 °C at x ~ 0.45, accompanied by an increase in the forward voltage drop (U_f) of the diodes. Small additions of Sb (y up to 0.05) do not significantly affect the static current–voltage characteristics of the diodes under investigation.

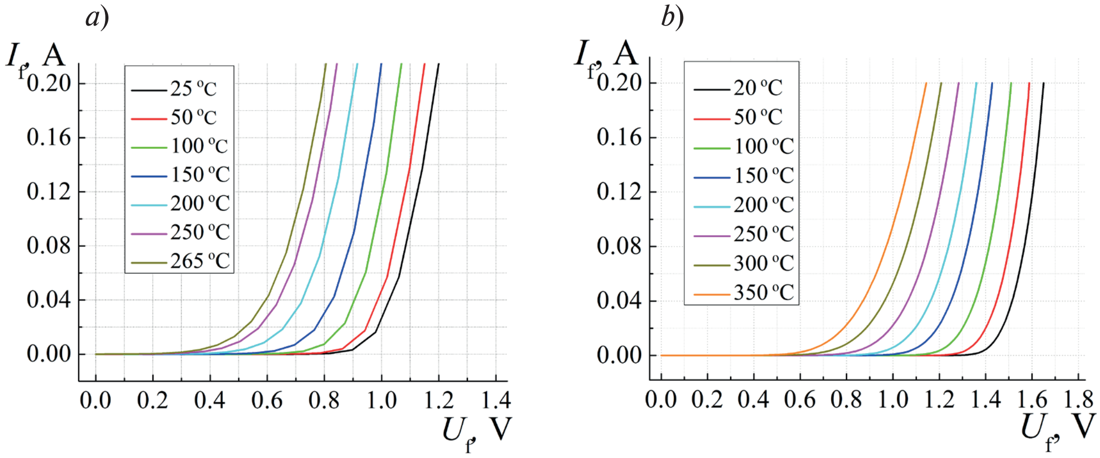

Fig. 1. Forward voltage drops in diodes with high-voltage $GaAs_{1-y}Sb_y$ p^0–i–n^0 layers with y up to 0.02 (a) and $Al_xGa_{1-x}As$ with x ~ 0.45 (b) at temperatures from 25 to 350 °C. Sample area S ~ 0.65 mm^2

Fig. 2 shows switching oscillograms of diodes with base layers $Al_xGa_{1-x}As$ and $Al_xGa_{1-x}As_{1-y}Sb_y$, demonstrating the influence of small Sb additives in AlGaAs layers, leading to the controlled formation of spatial defects, on the dynamics of diode switching. From Figure 2, it can be observed that the effective lifetime of nonequilibrium charge carriers τ_{eff} (assuming τ_{eff} ~ t_1) and, accordingly, the reverse recovery time of a diode with an $AlxGa_{1-x}As$ base layer is more than an order of magnitude greater than τ_{eff} of a diode based on an $Al_xGa_{1-x}As_{1-y}Sb_y$ layer (the figure compares diodes with approximately the same aluminum content in both base layers).

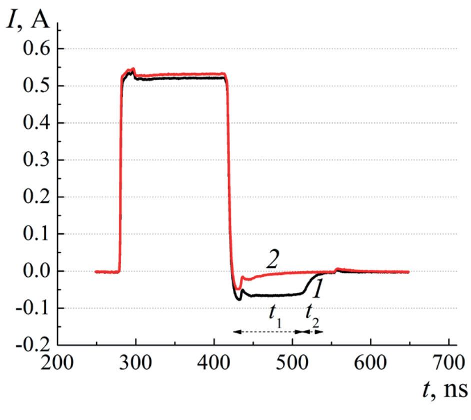

Fig. 2. Oscillograms of switching p–i–n diodes with base layers of $AlxGa_{1-x}As$ (*1*) and $Al_xGa_{1-x}As_{1-y}Sb_y$ (*2*) with x ~ 0.30 and y up to 0.05

Also, for some samples, the temperature dependences of the effective lifetime of nonequilibrium charge carriers τ_{eff} in the base layers of the diodes were determined (Fig. 3). The measurements showed a significant (up to five times) increase in the duration of the t_1 phase (and, accordingly, τ_{eff}) in the temperature range of 25–350 °C when switching the $Al_xGa_{1-x}As$ diode. However, the turn-off time of the GaAs diode did not depend so much on the temperature. This can be explained by the fact that in the layers under study, the lifetimes of nonequilibrium charge carriers are determined by different centers with deep levels. In GaAs p^0–i–n^0 junctions grown by the LPE method [6], τ_{eff} can be determined by hole traps HL2 and HL5 (related with a gallium vacancies), as well as electron trap EL2 related with the antisite defect of arsenic in the gallium site (arsenic in the gallium sublattice). In $Al_xGa_{1-x}As$ p^0–i–n^0 junctions (with $x \geq 0.21$), we believe that the relaxation time of nonequilibrium carriers, as well as its temperature dependence, are determined by the thermal capture of holes to the negatively charged level (DX) of the DX-center associated with residual donor impurities Se and Te [1].

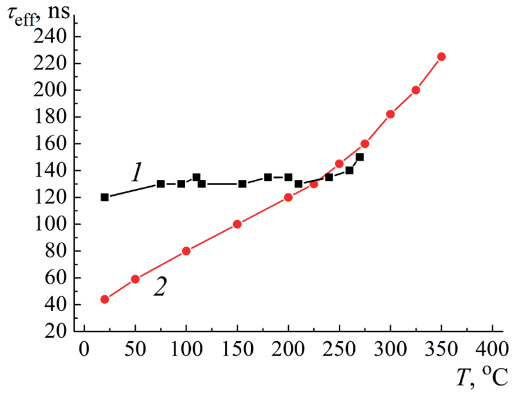

Fig. 3. Temperature dependences of the effective lifetime of nonequilibrium carriers in *p*–*i*–*n* diodes based on GaAs (*1*) and $AlxGa_{1-x}As$ with $x \sim 0.45$ (*2*)

Conclusion

In the research, the operating temperatures of diodes based on $AlxGa_{1-x}As$ and $AlxGa_{1-x}As_{1-y}Sb_y$ solid solutions were determined. The temperature range for which the diodes retain rectifying properties was found to be from 250–280 °C at $x = 0$ to at least 350 °C at $x \sim 0.45$, with an increase in the Al content in the layers. The current and temperature dependences of the forward voltage drops of diodes with $Al_xGa_{1-x}As_{1-y}Sb_y$ layers (with y up to 0.05) differed slightly from diodes with $Al_xGa_{1-x}As$ layers of the same aluminum composition. One notable result of adding small amounts of Sb to AlGaAs layers was a significant reduction in the reverse recovery time of high-voltage diodes based on them. The reverse recovery time decreased from 40–80 ns for diodes with AlGaAs base layers to 5–8 ns for AlGaAsSb structures with dislocations.

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