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Effect of temperature on the switching voltage of avalanche S-diodes

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The paper presents the results of an experimental study of the effect of temperature on the switching voltage of an avalanche S-diode made of GaAs with an iron impurity. It was found that an increase in temperature can lead to a decrease in the switching voltage at high switching frequencies (500 kHz). To analyze the effect, a simulation of double switching of an S-diode was carried out, and two different modes of its operation at a high pulse repetition rate were found.

Keywords: Avalanche breakdown, deep centers, gallium arsenide, power electronics, pulse technology.

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An avalanche S-diode is a semiconductor closing switch based on the collapsing domain effect [1–3]. The structure of an S-diode is similar to that of an avalanche bipolar transistor [3]. Its main differences are that the base region in the S-diode is obtained by compensating n-GaAs with a deep acceptor (iron), has a large resistivity (of the order of $10^5\,\Omega\cdot$cm) and thickness (more than $10\,\mu$m). This switch is effectively used to generate short current pulses in the pumping circuits of semiconductor lasers [3]. In terms of the $I/\Delta t$ ratio (I — current pulse amplitude, Δt — current pulse duration), the S-diode competes with other devices: field-effect transistors made of GaN [4,5], thyristors made of GaAs [6], and avalanche bipolar transistors made of Si [7]. Among these devices, the S-diode is the highest voltage diode, which causes a typical problem — self-heating during switching at frequencies from tens to hundreds of kHz. As shown in [3], the amplitude of current pulses drops by a factor of 3 as the frequency increases from 10 to 250 kHz. This effect has not been explained in detail, but has been attributed to an increase in temperature. This paper investigates the causes of this negative effect, finds a decrease in the switching voltage of the S-diode as the temperature increases when switching at high frequency, and proposes an explanation.

In this paper S-diodes from a batch with a switching voltage of 150–180 V are investigated. The S-diode was a $n^+{-}\pi{-}n^0{-}n^+$(substrate)-structure whose π-region was obtained by compensating n-GaAs with a deep acceptor (iron). The compensation was accomplished by diffusion into the original $n^+{-}n^-{-}n{-}n^+$-type epitaxial structure (Fig 1, a). The layer thicknesses were $d_{n^+} = 6\,\mu$m, $d_\pi = 11\,\mu$m, $d_{n^0} = 11\,\mu$m (detailed description is given in [3]). The switching logic of the S-diode as well as its structure are shown in Fig. 1, b. In operational mode, a voltage is applied to the S-diode at a rate of $\Delta V/\Delta t \approx 10^{10}$ V/s (positive polarity on the substrate). When the necessary conditions are reached, the S-diode switches to the ON-state [2,3].

The voltage across the S-diode was measured at point $1S$ using a high-impedance probe with a bandwidth of 200 MHz. The amplitude of the current pulses was measured in the pumping circuit of the semiconductor laser in a manner similar to the one described in [2]. In this case, commercially available chip lasers with a maximum efficiency of 3.6 W/A (up to 10 A in the linear region) were used as the load. The amplitude of current pulse was determined from the watt-ampere characteristic of the laser diodes from the measured optical power. In the experiment, the $SD{-}C{-}LD{-}L$ circuit was mounted on a massive aluminum base with active air cooling (a micro-fan with power consumption less than 0.5 W was used). At the same time, S-diode was attached to the base using thermally conductive adhesive through contact with the n^+-layer. When measuring the electrical parameters at a fixed switching frequency (500 kHz), the temperature of the base (T_M) was measured. To do this, a temperature sensor located at a distance of 3 mm from the S-diode was used. The temperature variation was achieved by adjusting the supply current of the micro-fan. The electrical characteristics was measured at the steady-state value of T_M.

The measurement results are shown in Fig. 2. We note two effects accompanying the temperature rise of T_M. First, the switching voltage (V_S) changes: there is a weak increase from 112 to 123 V, then a sharp drop to 86 V. Second, the switching efficiency decreases sharply when the switching voltage decreases: the current decreases by a factor of 3. Note that the exact value of the S-diode temperature (T) is unknown, and the growth of T can be judged only indirectly (from the measured temperature values of T_M).

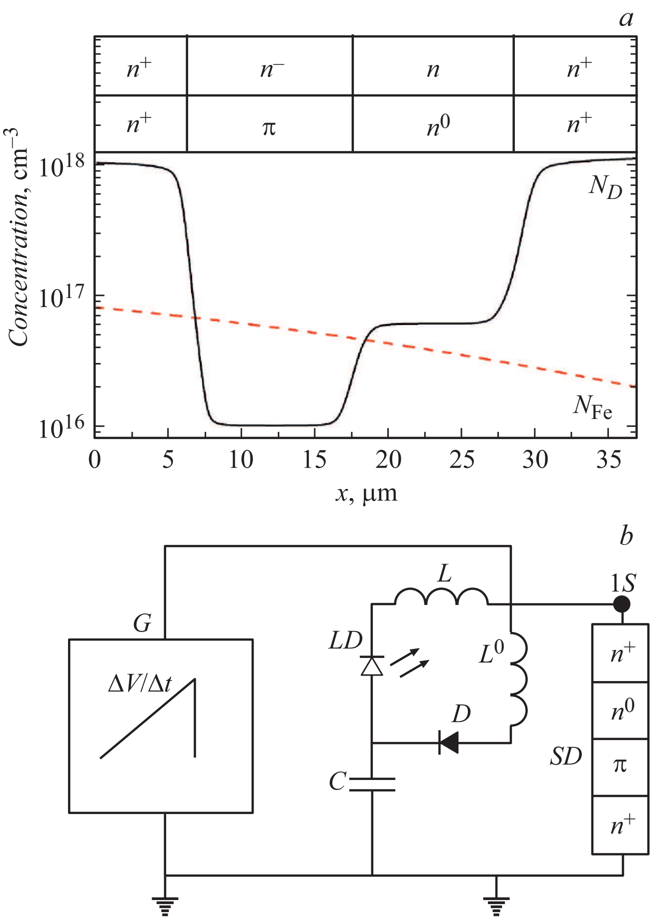

Figure 1. a — Impurity profiles of the shallow donor (N_D) and deep acceptor (N_{Fe}) in the structure. A schematic representation of the $n^+{-}n^-{-}n{-}n^+$- and $n^+{-}\pi{-}n^0{-}n^+$-structures is shown at the top. b — experimental circuit of the S-diode. G — triggering pulse oscillator, SD — S-diode, C — capacitor (200 pF), LD — laser diode, D — rectifier diode, L^0 — inductance 15 nH, L — spurious inductance 1 nH.

The effect of decreasing V_S as the temperature of T increases is described in the reference literature [8], but no explanation is provided. This effect appears anomalous because the switching is initiated by avalanche breakdown [2,3], the voltage of which generally increases as the temperature is increased. To explain the effect, this study simulates the switching of an S-diode in TCAD Sentaurus using the method described in [2]. The hydrodynamic model provided in [9] was used. In the simulation, the S-diode was triggered by two voltage pulses with an interval of 2 μs. In this approach, it was assumed that the amplitude of the second pulse on the S-diode corresponded to the switching voltage of the S-diode at 500 kHz. The field and temperature dependences of the ionization coefficients for electrons and holes were taken into account similarly to [9].

The simulation results are shown in Fig. 3. It can be seen that the temperature dependence of V_S has a kink: a weak increase in voltage is followed by a sharp decline at $T = 320{-}330$ K, after which V_S again increases weakly as T grows. When V_S decreases from 200 to 89 V, the amplitude of the current pulse decreases by a factor of 2.7. Analysis of the electric field profiles showed that up to the kink point, avalanche breakdown before switching occurs in the n-region, and after the kink point — at the boundary of the $n^-{-}n$-junction (insets in Fig. 3, a). In this case, the concentration of the charge captured at the deep centers (Fe atoms) during the voltage increase on the S-diode remains constant. To explain the two switching modes, the dynamics of the filling of iron centers in the time interval between the first and second triggering pulses voltage was considered.

It was found that after the first S-diode turn-on, an electron-hole plasma with a concentration of $10^{18}{-}10^{19}$ cm^{-3} is formed. Then there is a capture of holes on negatively charged iron centers, they become neutral. Electrons are captured by neutral iron centers much slower, since their capture cross section is small. As a consequence, the second switching (via 2 μs) occurs not in the $n^+{-}\pi{-}n^0{-}n^+$structure, but in the $n^+{-}n^-{-}n{-}n^+$-

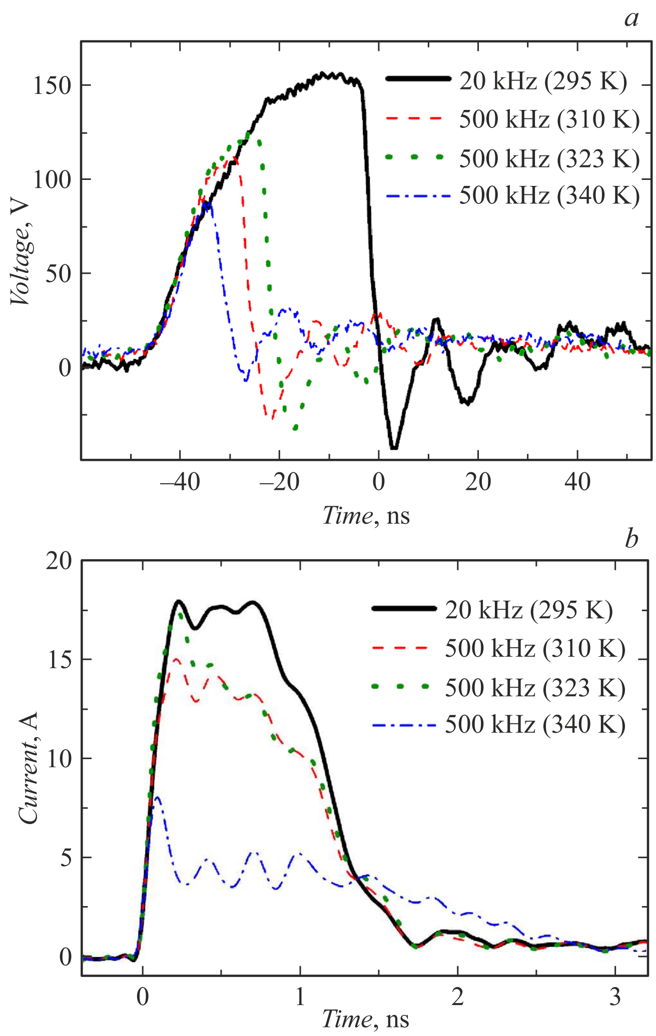

Figure 2. Experimental dependences of voltage across diode S- (a) and current across diode S (b) at different base temperatures T_M for two pulse repetition rates.

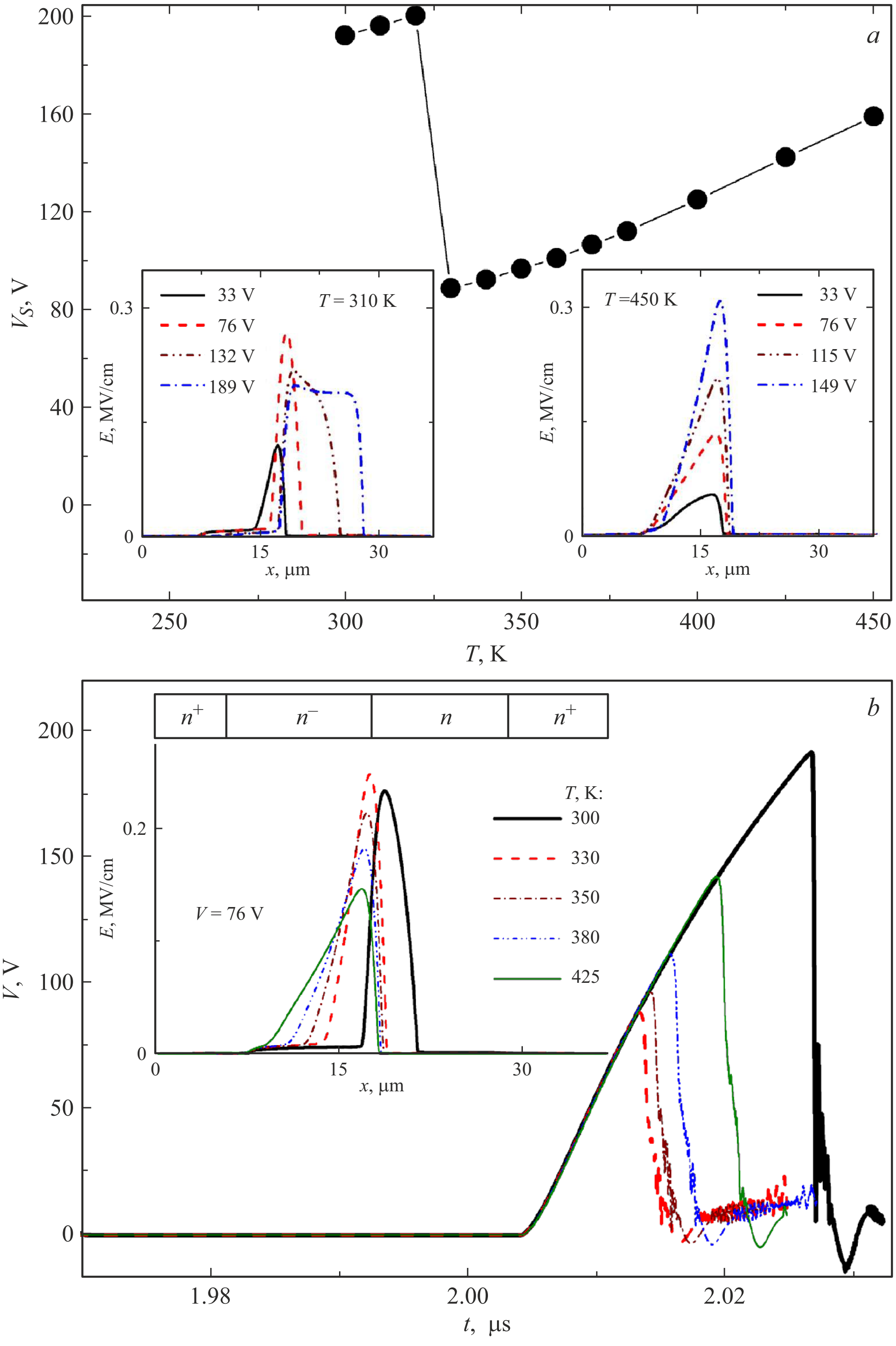

Figure 3. The calculated temperature dependence of the switching voltage (*a*) and the voltage across the *S*-diode at different temperatures (*b*). The insets (fragment *a*) show the calculated electric field profiles for different applied voltages at two temperatures, while the inset (fragment *b*) shows the electric field profiles at a fixed voltage of 76 V.

structure. This fact justifies an approach in which double switching is simulated within a single region. If a region with reduced switching voltage (n^+–n^-–n–n^+-structure) occurs in the structure after the first switch-on, it is the region where the current filament formation will occur at the second turn on of the *S*-diode. Indeed, in the experiment, the switching voltage at the first turn on is always higher than the switching voltage at the second turn on.

The level of compensation in the n^-- and n-regions depends on temperature: the higher T, the closer the charge distribution is to equilibrium at fixed time. At room temperature, during the second switching of the S-diode, the resistance of the $n^-{-}n$-junction is low, and the applied voltage is applied to the n-region (left inset in Fig. 3, a). This effect is due to electron injection from the $n^+{-}n^-$-junction: to screen the positive charge of ions in the n-region, a higher current density is required than in the n^--region. At $T \geq 330\,\mathrm{K}$ the resistance of the $n^-{-}n$-junction is high enough that the applied voltage leads to its avalanche breakdown (right inset in Fig. 3, a). Thus, an increase in temperature causes an increase in the resistance of the $n^-{-}n$-junction. The highest resistance is reached when the structure returns to the equilibrium state and becomes an $n^+{-}\pi{-}n^0{-}n^+$-structure (in this case, the concentration of free carriers is determined analytically using the formulas from [10]). Additional calculations have shown that the transition temperature from one mode to the other is sensitive to the values of the selected electron and hole capture cross sections. In this paper we present the results for the values $\sigma_n = 3 \cdot 10^{-19}\,\mathrm{cm}^{-3}$ and $\sigma_p = 1.5 \cdot 10^{-16}\,\mathrm{cm}^{-3}$.

The dynamic compensation effect described above also affects the growth of V_S as T increases. The inset to Fig. 3, b shows that an increase in temperature leads to an increase in the voltage at the n^--region and a decrease in the maximum electric field at the $n^-{-}n$-junction. Thus, in the avalanche S-diode, the increase in the avalanche breakdown voltage is related not only to the temperature dependence of the impact ionization coefficients, but also to the change in resistance due to the ionization of deep centers.

The presented analysis provides a qualitative description of the effect of V_S decrease as the temperature increases and allows justifying the need to cool the S-diode at high switching frequencies. In practice, exceeding a certain critical temperature should be avoided, otherwise the S-diode jumps into the mode of inefficient generation of current pulses. Accurate calculation of the temperature dependence of the switching voltage of the S-diode requires knowledge of the temperature and field dependences of the cross sections of the charge carriers capture on deep centers, as well as the concentration of charged centers in the areas of current filament formation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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