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Anomalous Dynamics of the Residual Voltage across a Gallium-Arsenide Diode upon Subnanosecond Avalanche Switching

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Abstract—A qualitative difference between high-voltage gallium-arsenide diodes and similar silicon devices is found experimentally upon ultrafast switching in the delayed avalanche breakdown regime. It is shown that, following switching, a gallium-arsenide diode remains in a highly conductive state throughout the entire duration of the applied voltage pulse and the recovery of the reverse voltage across the *p*–*n* junction due to the dispersal of nonequilibrium electron–hole plasma is not observed. In the same interval of time (2 ns in our experiment), a silicon diode passes completely into a blocking state. The residual voltage amplitude for a gallium-arsenide diode is an order of magnitude lower than that for a silicon device. The discovered effect is similar to a known effect of "sticking" of gallium-arsenide diode switches (the lock-on effect), which are triggered by a laser pulse, in a conductive state.

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The effect of delayed avalanche breakdown of high-voltage diodes consists in a subnanosecond transition of the structure from the blocking state into the conducting one upon a rapid increase in the reverse voltage. This delayed avalanche breakdown has already been observed in structures based on silicon [1, 2] and gallium arsenide [3–6]. Silicon structures are widely used in power pulse electronics for shaping kilovolt voltage drops with a duration of 100 ps or less [7–9]. The present paper details the results of a comparative experimental study of subnanosecond switching of high-voltage gallium-arsenide and silicon diodes with close stationary breakdown voltages and geometrical parameters. The obtained results do not only confirm the feasibility of shaping kilovolt voltage drops with a duration of about 100 ps with the use of gallium-arsenide diodes, but also reveal a previously unknown qualitative difference in the behavior of gallium-arsenide and silicon structures after ultrafast switching.

The experimental setup incorporated a pulse generator, a resistive coupler, a system of ultrawideband attenuators, and a wideband oscillograph. The resistive coupler was part of a high-quality coaxial measurement circuit with wave impedance $\rho = 50\ \Omega$ and also served as a holder for the studied structure. The presence of this coupler rendered it possible to measure simultaneously and independently voltage $U^{\Sigma}(t)$ across the structure together with series-connected load $\rho = 50\ \Omega$ and the voltage at load $U^{\rho}(t)$. This allowed us to determine both the voltage across the studied structure and the current $I(t) = U^{\rho}/\rho$ flowing through it with a time resolution of better than 50 ps. The setup is described in more detail in [10]. Just as in [10], bell-shaped voltage pulse $V(t)$ applied to the diode and series-connected load ρ in our experiments had an amplitude of 3.7 kV and a half-width of 2.5 ns.

The measurements were performed for gallium-arsenide p^+–p_0–n_0–n^+ structures with their p_0 and n_0 regions fabricated via liquid-phase epitaxy. The total width of these regions was about 100 μm. The ratio of the thicknesses of p_0 and n_0 regions was defined by the concentration of residual acceptor (Si) and donor (O) impurities and the profile of concentration of deep levels [11]. The effective doping level in the p_0–n_0 junction region was lower than 10^{13} cm^{-3}. Structure diameter $d^{\mathrm{GaAs}} \approx 1$ mm. Measured stationary breakdown voltage $U_b^{\mathrm{GaAs}} \approx 600$ V. The smooth increase in current with increasing voltage indicated that the stationary breakdown was of a surface nature. Silicon p^+–n–n^+ structures with a similar diameter $d^{\mathrm{Si}} \approx$ 1.1 mm and the stationary breakdown voltage $U_b^{\mathrm{Si}} \approx$ 1 kV were chosen for comparison. The structures were fabricated from silicon grown by the Czochralski technique, and the *p*–*n* junction was formed through boron diffusion. These diodes exhibited a sharp increase in current close to the stationary breakdown voltage. This suggested that the breakdown was bulk in nature.

When the delayed avalanche breakdown was studied, bell-shaped voltage pulse $V(t)$ was applied to the

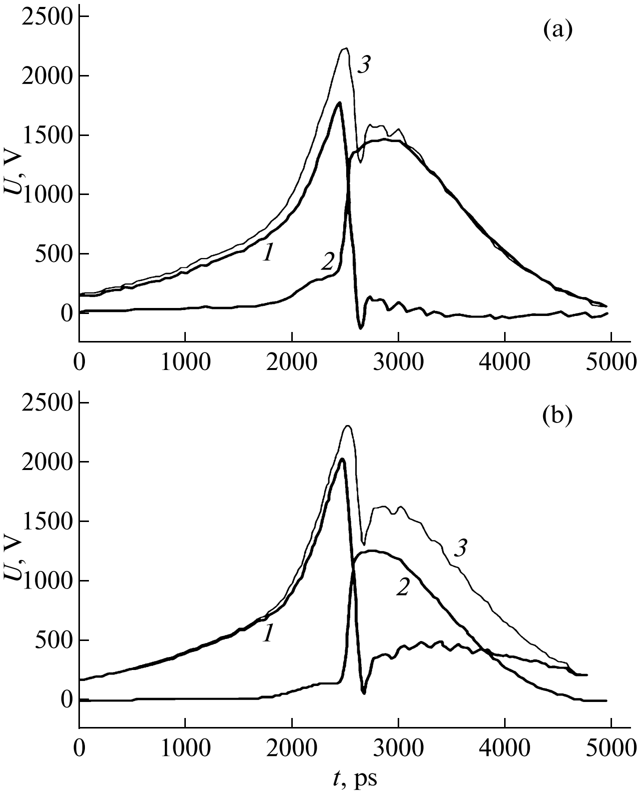

Fig. 1. Switching dynamics for (a) gallium-arsenide and (b) silicon diodes. The voltage across the structure $U^D(t)$ (curve *1*), the voltage at ohmic load $U^\rho(t)$ (curve *2*), and the voltage across the device with the load $U^\Sigma(t) = U^D + U^\rho$ (curve *3*) are indicated. The values of U^Σ and U^ρ were measured directly and independently. The current flowing through the structure was determined using the equation $I(t) = U^\rho/\rho$, where $\rho = 50\ \Omega$.

diode together with a series-connected load (the coaxial circuit resistance $\rho = 50\ \Omega$). Figure 1 shows the voltage $U^\Sigma(t)$ across the device together with the load and the voltage at load $U^\rho(t)$ obtained via direct measurements and the device voltage $U^D(t) = U^\Sigma - U^\rho$. The voltage at load was proportional to the current flowing through the structure. The gallium-arsenide diode switching was initiated at $U^m_{\mathrm{GaAs}} \approx 1660$ V. The switching time measured with reference to the voltage drop level 0.9–0.1 equaled 140 ps (see Fig. 1a). The measurement circuit contained four attenuators with an intrinsic rise time of 30 ps and an oscillograph with an intrinsic rise time of 20 ps. Assuming the measured time to be a root-mean-square value of the rise times of all circuit elements (including the studied diode), we obtain a device switching time of no more than 125 ps.

Similar ultrafast switching parameters were obtained for the silicon structure: switching was initiated at about 2000 V, and the measured switching time was 120 ps (see Fig. 1b). Thus, the delayed avalanche breakdown of an "overvoltaged" structure was observed both for gallium-arsenide and silicon devices. This breakdown led to an ultrafast transition of the structure to the conducting state and was accompanied by the formation of a kilovolt voltage drop at load with a duration of about 100 ps.

However, the voltage dynamics after ultrafast switching of gallium-arsenide and silicon structures exhibited previously unknown qualitative differences. First, the residual voltage across a gallium-arsenide diode after switching was an order of magnitude lower than that for a silicon diode. Second, the residual voltage across a gallium-arsenide diode did not tend to increase throughout the entire duration of the applied voltage pulse. Let us discuss these differences in more detail.

The measured residual voltage across a gallium-arsenide diode amounted to several tens of volts (see Fig. 1a), and its amplitude was comparable to the accuracy of the residual voltage measurement in our experiment. This accuracy was limited, first, by damped oscillations in the measurement circuit caused by a sharp kilovolt voltage drop at the diode upon switching. Second, device voltage U^D was defined as the difference between two values (U^Σ and U^ρ) that were measured simultaneously with the use of two different oscillograph channels. These values for a gallium-arsenide structure were close to each other after switching. The residual voltage across a silicon device amounted to several hundred volts (see Fig. 1b). Such residual voltage values are typical for silicon p^+–n–n^+ structures with an "abrupt" *p*–*n* junction [10].

The gallium-arsenide diode voltage dynamics did not show any signs of recovery of the voltage across the reverse-biased *p*–*n* junction after avalanche switching (see Fig. 1a), while the silicon structure clearly exhibited such signs (see Fig. 1b). The effective resistance of the silicon structure increased monotonically after switching, and the reverse voltage recovered completely after breakdown in just 2 ns. The reduction in voltage across the device visible in Fig. 1b was induced exclusively by a reduction in applied voltage $V(t)$. This pattern agrees well with the generally accepted concepts of drift extraction of excess carriers from a reverse-biased structure. On the contrary, the gallium-arsenide structure resistance did not vary throughout the entire pulse duration, and the current flowing through the structure was defined by series resistance of the coaxial circuit ρ. This anomalous behavior of a gallium-arsenide diode after switching is similar to a well-known effect of "sticking" of optical switches based on gallium-arsenide diodes in a conductive state (the lock-on effect) [12]. Photogeneration of carriers by radiation from a dense electron–hole plasma produced via impact ionization may be of great importance in gallium-arsenide diodes [13]. The Reabsorption of recombination radiation [13] may result in a more uniform distribution of the electron–hole plasma over the volume of the structure. However, this mechanism cannot maintain conduction after the impact ionization subsides.

The retention of a low residual voltage value over a period of time that is longer than the drift plasma extraction time is suggestive of the presence of a plasma production mechanism that operates after ultrafast switching even at low levels of the average electric field. Such a mechanism has long been searched for with the purpose of explaining the lock-on effect in optical switches based on GaAs the switching of which is initiated by a laser pulse [12]. The physical conditions in which such an optical switch is placed after switching are identical to the conditions created in our experiment: a reverse-biased diode filled with conductive plasma is connected in series with load to an external source. The lock-on effect is observed only in structures based on materials with negative differential electron conductivity [12]. The retention of a conductive state was explained by the spontaneous emergence of narrow collapsing domains of strong electric field (with the field strength being sufficiently high for intense impact ionization) in a recent paper [14]. Such domains were predicted for a gallium-arsenide avalanche transistor as a mechanism of its subnanosecond switching [15]. In order for the domains to emerge, the average electric field strength should exceed the threshold of negative electron mobility in GaAs (3–4 kV/cm). If the base length is 100 μm, this average field value corresponds to a residual voltage of ~30 V. This does not contradict the results of our measurements.

In our experiment, the time of measurement of the voltage across a diode after switching was limited by the duration of the bell-shaped $V(t)$ pulse and was about 2 ns. The study of the residual voltage dynamics over longer times will be the subject of our further research. The discovered effect may be of great practical importance, since it opens the possibility of shaping rapidly rising current pulses (with their duration not being limited by the nonequilibrium electron–hole plasma dispersal time and the recovery of the blocking capacity of a p–n junction) with the use of gallium-arsenide diodes.

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