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Admittance characteristics of sensors based on chromium-compensated gallium arsenide

© M.S. Trofimov, N.N. Yakovlev

Tomsk State University,
Tomsk, Russia

E-mail: mikhail.trofimov@mail.tsu.ru

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An experimental study of the admittance characteristics of sensors based on chromium-compensated gallium arsenide (HR-GaAs:Cr) with Ni and Cr barrier contacts in the temperature range of $30-280\,^\circ$C has been performed. The capacitance-voltage and voltage-siemens dependencies at a frequency of 1 MHz are analysed. It is found that, within the temperature range of $30-150\,^\circ$C, the HR-GaAs:Cr sensors operate in flat capacitor mode, where capacitance is independent of voltage. Within the temperature range of $150-280\,^\circ$C, the sensors transition to operating in Schottky barrier mode. It is demonstrated that, within the $230-280\,^\circ$C range, the appearance of kinks in the capacitance-voltage dependencies is linked to the occurrence of tunnel electrical breakdown in the sensors. It is found that, with increasing voltage, the conductivity of the sensors decreases and reaches the saturation site as a result of depletion of their active region by electrons. The chromium activation energy in GaAs was calculated from the temperature dependence of the sensors conductivity, yielding $E_a = 0.81$ eV, which is in good agreement with the literature data.

Keywords: semiconductor sensors, HR-GaAs:Cr, capacitance-voltage dependence, voltage-siemens dependence.

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1. Introduction

The urgency of creating semiconductor ionizing radiation detectors is due to the need to develop medical X-ray diagnostic systems and research infrastructure for synchrotron radiation sources. Earlier, the Center for Research and Development „Advanced Technologies in Microelectronics" TSU developed a technology for obtaining detector-quality material based on gallium arsenide compensated with chromium by the diffusion method [1], which formed the basis for the production of semiconductor sensors. The resulting HR-GaAs:Cr structures (HR — high resistivity) have a uniform electric field distribution over the thickness of the active region, charge collection efficiency of more than 90%, resistivity up to 10^9 Ohm $\cdot$ cm and a thickness of more than 1 mm [2–5]. It has been shown in Refs. [6–9] that multi-element sensors based on HR-GaAs:Cr well meet the requirements for manufacturing semiconductor detectors for X-ray imaging systems, including for synchrotron experiments [10–13].

Further development of semiconductor detector manufacturing technology requires fundamental research on the mechanisms of charge carrier transport in sensors and their electrophysical characteristics. One of the widely used methods for these purposes is the method of admittance spectroscopy. This method is based on the measurement of the capacitive and active components of the conductivity of a semiconductor structure on an alternating signal when a constant offset is applied [14,15]. Measuring the capacitive component of admittance allows us constructing a capacitance-voltage characteristic of the structure, which can be used to determine a number of important electrophysical characteristics: the height of the potential barrier at the metal-semiconductor interface, the depletion voltage, concentrations of deep and small impurity centers, their capture cross sections and recharge times. Measuring the active component of conductivity at different temperatures makes it possible to determine the activation energy of impurities in a semiconductor, and measuring the volt-Siemens characteristic makes it possible to obtain information about generation-recombination processes.

In this paper, the capacitive and active components of the admittance of HR-GaAs:Cr sensors with barrier contacts were measured over a wide temperature range at a frequency of 1 MHz. A detailed analysis of the capacitance-voltage and volt-siemens characteristics of the sensors has been carried out.

2. Materials and methods

Sensors based on gallium arsenide grown by the Czochralski method and chromium-compensated by the diffusion method (HR-GaAs:Cr) were studied in this experiment. The size of the sensors was $3 \times 3\,\text{mm}^2$, and the thickness was $500\,\mu$m. The electrical contacts of the sensors were made of chromium (Cr) and nickel (Ni) deposited on both sides by electron beam spraying in the form of continuous layers with a thickness of 90 and 150 nm, respectively. The activation energy method was used to measure the height of the potential Schottky barrier at the metal-semiconductor interface. For this purpose, the volt-ampere characteristics (VAC) of the samples were measured using a Keithley 2636A measuring source in the temperature range of 30−70 °C a step of 5 degrees. Saturation currents I_0 for each temperature were determined by conducting a linear extrapolation of the VAC to $U = 0$ V. Plotting the dependence in coordinates $\ln(I_0/T^2)$ on $1/kT$, where k is the Boltzmann constant, the values of the height of the Schottky barriers were determined from the tangent of the angle of inclination of the approximating straight line. As a result, $\Phi_b = 0.67 \pm 0.03$ eV in samples with Cr-based contacts and $\Phi_b = 0.72 \pm 0.01$ eV in samples with Ni contacts. Thus, the experiment studied symmetric structures of the type Me−HR-GaAs:Cr−Me (where Me is a metal contact).

The sensors were placed in a Nextron microprobe 4-channel station with the ability to set the temperature from room temperature to 750 °C with an accuracy of 0.1 °C. The heating temperature of the sensors varied in the range 30−280 °C. The admittance characteristics of the sensors were measured on an E7-12 *RLC* meter in parallel equivalent circuit mode, which was connected to a microprobe station. The value of the constant voltage applied to the sensors varied during the measurement in the range of 0−39 V. The frequency and amplitude of the measuring signal were 1 MHz and 25 mV, respectively. In one measurement cycle, consisting of applying a constant voltage and a small alternating signal to the test samples, the device separately measured the active and capacitive components of the admittance in an automated mode. The measurement results were output to a computer in the form of capacitance-voltage $C(U)$ and volt-siemens $G(U)$ characteristics.

3. Definition of the frequency domain of measurement

From the theory of measuring $C(U)$ characteristics of structures with deep centers, it is known that, depending on the frequency (or period) of the measuring signal, low-frequency (LF) and high-frequency (HF) capacitances are distinguished [16]. The low-frequency capacity criterion is the inequality $T \gg \tau$, where T — the period of the measuring signal, τ — the recharge time of the deep centers, which determines the value of the frequency (or period) of the measuring signal at which the deep center „manages" to respond to changes in the electric field and contributes to the capacitance. The criterion for RF capacitance is the inequality $T \ll \tau$, in which the deep centers do not have time to respond to changes in the electric field and do not contribute to the measured capacitance.

The recharge time of deep centers in semiconductors is mainly determined by the emission of electrons into the conduction band or holes into the valence band, the flow times of which are significantly higher than the capture times of carriers from the allowed bands. This is due to the presence of a potential barrier between the deep center and the allowed band, which must be overcome by carriers due to thermal energy received from phonons or from an electric field.

When the magnitude of the electric field applied to the semiconductor is relatively small, the emission of charge carriers into the allowed bands is thermionic, the flow time of which is determined by an expression written in general form for electrons and holes:

$$\tau_{e,h} = 1/\sigma_{e,h}\upsilon_{th(e,h)}N_1, \tag{1}$$

where $\sigma_{e,h}$ is the capture cross section of electrons and holes by deep centers, $\upsilon_{th(e,h)}$ is the thermal velocity of electrons and holes, N_1 is the concentration of charge carriers reduced to the level of deep centers (for electrons it is written as n_1, and for holes as p_1).

The expressions for n_1 and p_1 have the following form:

$$n_1 = N_c \exp(-E_{dd}/kT), \tag{2a}$$

$$p_1 = N_v \exp(-E_{da}/kT), \tag{2b}$$

where N_c and N_v is the effective densities of quantum states in the conduction band and valence band, respectively, E_{dd} and E_{da} is the activation energies of deep donor and acceptor centers, accordingly, k — Boltzmann constant, T is the temperature.

The effective densities of quantum states in the allowed bands and the thermal velocities of charge carriers have a weak power-law dependence on temperature: $N_{c.v} \sim T^{3/2}$; $V_{th(e,h)} \sim T^{1/2}$. It is known from the literature that the capture cross sections of deep centers and their activation energies depend on temperature. At least two types of deep centers are present in the studied HR-GaAs:Cr structures: chromium, which is a deep acceptor trap center for holes in the ionized state, and $EL2$-centers, which are deep donors that have a high electron capture cross section in the ionized state. The concentration of chromium and $EL2$-centers in the studied samples was of the order of 10^{17} and $3 \cdot 10^{15}$ cm^{-3}, respectively. According to the literature data from Ref. [17], the cross section of hole capture on negatively charged chromium centers $\sigma_h^{\text{Cr}-}$ and their activation energy depend on temperature, as:

$$\sigma_h^{\text{Cr}-} = 10^{-16}\exp(-0.2/kT)\ [\text{cm}^2], \tag{3a}$$

$$E_{\text{Cr}} = 0.81 - (3 \cdot 10^{-4}T^2)/204 + T + kT\ln(0.93)\ [\text{eV}]. \tag{3b}$$

The temperature dependences of the electron capture cross section at $EL2$-centers and their activation energy have the form:

$$\sigma_e^{EL2+} = 6 \cdot 10^{-15}\exp(-0.66/kT)\ [\text{cm}^2], \tag{4a}$$

$$E_{EL2} = 0.759 - 2.37 \cdot 10^{-4}T\ [\text{eV}]. \tag{4b}$$

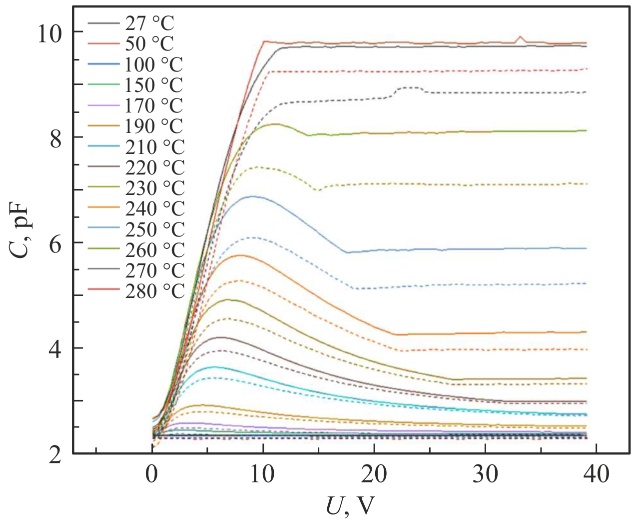

Figure 1. $C(U)$ Characteristics of HR-GaAs:Cr sensors with contacts based on Ni (solid) and Cr (dotted).

Using expressions (1)−(4) the emission times of holes from deep chromium centers and electrons from $EL2$-centers in the studied temperature range were calculated. It was found that even at a temperature of 280 °C, the emission time of electrons from $EL2$-centers (τ_{El2}) and holes with levels of Cr (τ_{Cr}) is significantly longer than the period of the measuring signal ($\tau_{EL2} = 5\,\mu$s, $\tau_{\mathrm{Cr}} = 50\,\mu$s). To measure the low-frequency capacitance caused by deep centers, it is necessary that the period of the measuring signal T be at least 2 times shorter than the recharge time of deep centers [18]. Thus, to a first approximation, it can be assumed that in this work a measurement of the high-frequency capacitance due to ions of small impurities was carried out, which does not include the capacitance due to the ionized centers Cr and $EL2$.

4. Experimental results

4.1. $C(U)$ characteristics of HR-GaAs:Cr sensors

4.1.1. Experimental data

Figure 1 shows the capacitance-voltage $C(U)$ characteristics of HR-GaAs:Cr sensors in the temperature range of 27−280 °C. Analysis of these results shows that $C(U)$ characteristics of sensors with Ni and Cr contacts behave identically. When the temperature of the sensors changes in the range of 30−100 °C, there is no dependence of capacitance on voltage. The capacitance value of all sensors is about 2 pF, which exactly matches the value of the capacitance calculated using the flat capacitor formula:

$$C = \varepsilon\varepsilon_0 S/d, \quad (5)$$

where $\varepsilon = 11.8$ is the relative permittivity of GaAs, ε_0 — electrical constant, S is the sensor area, d — its thickness.

When the temperature of the sensors increases to 150 °C, their capacitance depends on the voltage, which behaves in a specific way. 3 sections appear on the $C(U)$ sensor characteristics in the temperature range of 150−220 °C. In the voltage range of 0−10 V, a region of capacitance growth is observed, the maximum of which shifts with increasing temperature to the region of high voltages and at a temperature of 260 °C corresponds to 10 V. A description of the physics of the appearance of areas of initial capacitance growth in various semiconductor structures is presented in Refs. [19–23]. The authors of Refs. [19,20] observed an initial increase in capacitance on the $C(U)$ characteristics of Schottky diodes based on $NiSi_2$/Si(111) and nGaAs structures and attributed them to the presence of a high density of surface states at the interface boundaries. It was shown in Ref. [21] using the example of a Schottky diode based on n-Si, that the increase in capacitance is not associated with interface states at the metal-semiconductor interface, but is caused by the injection of non-basic charge carriers (holes) from the Schottky contact into the semiconductor volume, leading to the appearance of a diffusion tank. The authors of Ref. [22] theoretically and experimentally prove that the key reason for the appearance of an increase and maximum capacity is the serial resistance (R_s) of the device. Using the example of a GaAs-based Schottky diode, the authors of Ref. [23] refute the results obtained by the authors of Ref. [22]. They prove that the observed capacity maxima are not caused by the sequential resistance R_s of the device, but are the result of defective levels (traps) induced by the RF-sputtering process near the metal-GaAs boundary.

Further, after the capacity maxima, a period of decline and saturation is observed. It is important to note that the capacitance decrease occurs according to the law $C \propto \exp(-a + b/U + c)$, where a, b, c are the fitting constants, U is the voltage. This indicates a complex type of concentration profiles of small impurities in the studied samples. Accordingly, to determine the concentration of impurities, the use of theories of smooth or sharp $p-n$transitions is incorrect and requires numerical modeling.

Saturation occurs at approximately a voltage of 30 V in the temperature range of 150−220 °C the output of $C(U)$ characteristics. Starting from 230 °C, a characteristic kink appears on the $C(U)$ sensor characteristics, after which capacity saturation abruptly occurs. The voltage corresponding to the fracture on the $C(U)$ characteristics decreases with increasing temperature and averages 10−12 V at the temperature of 280 °C. Moreover, there is no decrease of capacitance at all at temperatures of 270 and 280 °C and saturation immediately sets in after growth.

4.1.2. Physics of the occurrence of fractures on $C(U)$ characteristics

It has been hypothesized that the appearance of fractures in the $C(U)$ sensor characteristics in the high temperature region is associated with the occurrence of an electrical

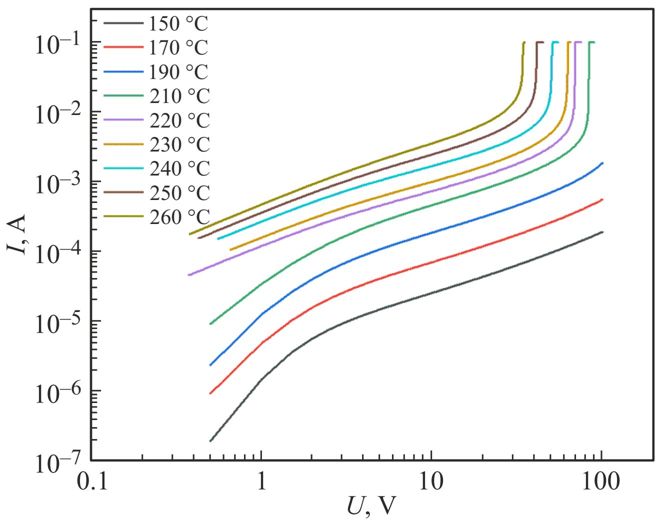

Figure 2. VAC HR-GaAs:Cr sensors with Ni-based contacts in the temperature range 150–260 °C.

breakdown, leading to a narrowing of the space charge region (SCR) due to the appearance of a high concentration of free carriers. To confirm this, the VAC of sensors with Ni-based contacts was measured and analyzed at temperatures of 150–260 °C (Figure 2).

It is known that the current-voltage dependence in semiconductor structures can be represented as $I \sim U^b$, where b is an indicator of the degree of nonlinearity of the VAC. At $b < 1$ the VAC is sublinear, which is typical for barrier structures, at $b = 1$ the VAC is linear and the current in the structure obeys Ohm's law, and at $b > 1$ the characteristic is superlinear, which usually indicates the occurrence of electric breakdown. The results show that the sensor has no electrical breakdown at temperatures of up to 170 °C and a voltage of 100 V (the nonlinearity coefficient is $b < 1$ and averages 0.7–0.8). An ultra-linear increase in current with a non-linearity index $b = 1.4$ is observed at 190 °C in a range of 50–100 V, which indicates the occurrence of a breakdown. Starting from 210 °C, there is a strong superlinear current growth after 80 V, where the nonlinearity coefficient b is 20–35. Breakdown begins at approximately 30 V at a temperature of 230 °C, which exactly corresponds to the stress of the fracture appearance on the $C(U)$ sensor characteristics. As the temperature increases, the breakdown and fracture stress on the $C(U)$ characteristics shifts to lower values and is less than 30 V at the temperature of 260 °C.

It is known from the literature that during tunnel breakdown, with increasing temperature, the breakdown voltage decreases and the curves shift to the left, which is observed in Figure 2 [14]. As shown above, the activation energies of chromium and *EL*2-centers in GaAs depend on temperature, and decrease with its increase according to linear and quadratic laws. In addition, with increasing temperature, the GaAs band gap decreases according to the law described by the following expression:

$$E_g = E_{g0} - \alpha T^2/(\beta + T), \quad (6)$$

where $E_{g0} = 1.519$ eV is the band gap width at 0 K, α and β are the temperature coefficients, the values of which for GaAs according to the latest data are $5.61 \cdot 10^{-4}$ eV/K and 266 K respectively [24].

Since the depth of the impurity centers is less than the band gap, the probability of impurity tunnel junctions with increasing temperature will be higher than its own. Thus, the observed kinks on the $C(U)$ characteristics of the HR-GaAs:Cr sensors in the region of 230–280 °C is most likely associated with the occurrence of tunnel breakdown as a result of a decrease in the activation energy of deep centers.

4.2. Active conductivity of HR-GaAs:Cr sensors. $G(U)$ characteristics

Figure 3 shows the volt-Siemens $G(U)$ characteristics of HR-GaAs:Cr sensors, measured in the temperature range of 30–280 °C. It can be seen that in the entire voltage range there is a decrease in the active conductivity of sensors, whereas an increase is observed in the range of 0–10 V at $C(U)$ characteristics. A very weak increase, on the order of several percent of the maximum value is observed in the range of 230–280 °C after the drop, which can be considered as the entry of conductivity to the saturation region. Moreover, a break also appears on the $G(U)$ characteristics in the temperature range of 250–280 °C, which was observed on the $C(U)$ characteristics of sensors as a result of the tunnel breakdown.

The decrease in conductivity and its exit to the saturation site with an increase in voltage can be explained by Ref. [25] which proposed an analytical model of current flow in structures based on GaAs:Cr with barrier contacts. The

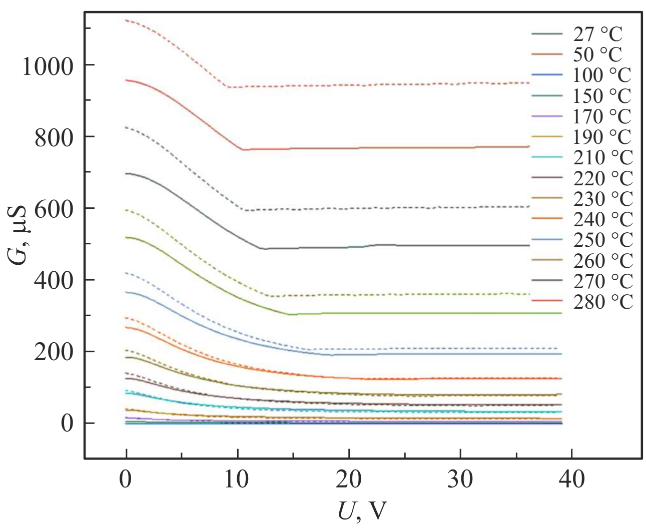

Figure 3. $G(U)$-characteristics of HR-GaAs:Cr sensors with contacts based on Ni (solid) and Cr (dotted).

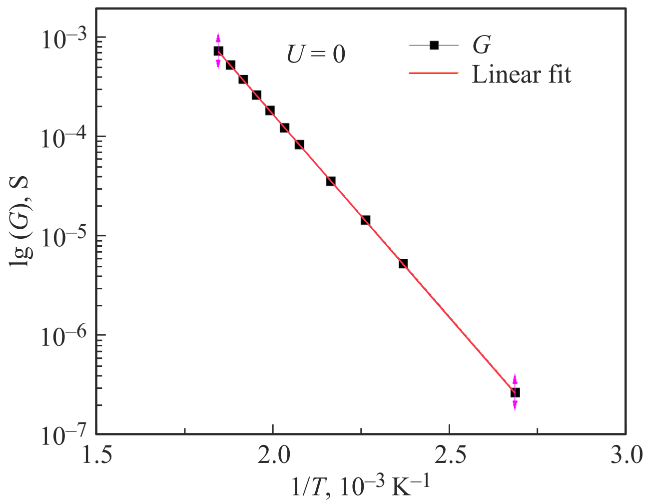

Figure 4. The temperature dependence of the active conductivity of the HR-GaAs:Cr sensor, plotted in Arrhenius coordinates.

model shows that with an increase in the applied voltage in the GaAs:Cr structure, a transition from an electron-hole type of conductivity to a hole type (inversion of the type of conductivity) occurs. It is shown that the anode contact is anti-blocking for holes and acts as an ohmic contact, while the cathode contact is a barrier contact for electrons, which leads to depletion of the active region of GaAs.:Cr of the sensor by electrons. At a certain voltage, most of the electrons are confined by an inversely displaced barrier, and holes are mainly involved in current transfer.

Since the conductivity is proportional to the concentration of charge carriers, this effect can lead to a decrease in the active conductivity of the sensor with increasing voltage and reaching saturation.

It is known that the temperature dependence of the active conductivity of a semiconductor structure can be described by the Arrhenius equation:

$$G(T) = A\exp(-Ea/kT), \qquad (7)$$

where A is a parameter that weakly depends on temperature (can be considered a constant); E_a is the activation energy of the impurity.

When constructing the dependence of the decimal logarithm of conductivity on $1/T$ (Arrhenius coordinates), a linear function is obtained, the tangent of the slope angle ($\mathrm{tg}\,\alpha$) of which characterizes the activation energy of the impurity:

$$E_a = B\,\mathrm{tg}\,\alpha k, \qquad (8)$$

where is the coefficient $B = 2.3$, which appears when taking the decimal logarithm of the exponent, k is Boltzmann constant.

Figure 4 shows the temperature dependence of the HR-GaAs:Cr sensor conductivity, plotted in Arrhenius coordinates. The value of the activation energy is $E_a \approx 0.81$ eV, which corresponds with good accuracy to the activation energy of the chromium impurity in GaAs.

5. Conclusion

Experimental data on the admittance characteristics of ionizing radiation sensors based on HR-GaAs:Cr with barrier contacts over a wide temperature range have been obtained for the first time. It is established that up to 150 °C the capacitance of HR-GaAs:Cr sensors is not observed on voltage, the structure works like a flat capacitor. With a further increase in temperature, a specific $C(U)$ dependence appears, which is probably due to an increase in the concentration of impurity ions, resulting in a transition to the Schottky barrier mode with an inhomogeneous distribution profile of impurity ions. The observed initial increase in capacity can presumably be associated with both the influence of surface conditions and the appearance of additional diffusion capacity, which requires additional numerical modeling. A correlation was found between the capacitance-voltage and volt-ampere characteristics of sensors in the temperature range of 230−280 °C. It is shown that the observed fractures on the $C(U)$ characteristics of sensors are associated with the occurrence of an electrical breakdown, which in all its features corresponds to a tunnel breakdown.

A decrease in conductivity over the entire temperature range and its saturation was detected as a result of measuring the voltage-Siemens $G(U)$ characteristics of the sensors. It is established that this dependence is associated with an inversion of the type of conductivity of the sensor as a result of depletion of its active region by electrons. By constructing the conductivity of the HR-GaAs:Cr sensor from the temperature in the Arrhenius coordinates, the activation energy of the chromium impurity was calculated, which was $E_a = 0.81$ eV, which is in good agreement with the known experimental data.

In the future, numerical simulations of $C(U)$ and $G(U)$ characteristics of HR-GaAs:Cr sensors will be performed, which will allow for a more detailed explanation of the observed dependencies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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