P2-19: Characterization and Modeling of Ge Film Thermometers for Low Temperature Measurements

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Abstract
Cryogenic resistance thermometers composed of Ge films on GaAs substrates have been produced and characterized. They are able to measure temperature over a wide range, from 0.03 K to 400 K. Behavior of these thermometers in magnetic fields and under gamma irradiation has been studied. The low-temperature conduction and magneto-resistance mechanisms of Ge-films used as a sensitive material for thermometers have been analyzed.

Keywords
Low-temperature thermometers, resistance thermometers, Ge films, localization.

INTRODUCTION

Resistive and diode sensors are most often used to measure low temperatures. A review of the state of the art in cryogenic thermometry can be found in ref. [1, 2]. As a rule, diode temperature sensors are not used for temperature measurement in a magnetic field because the magnetic field causes a large error in the thermometer reading. Some types of resistive sensors can be used for temperature measurement in magnetic fields [3-7]. Development of thermometers characterised by high measurement accuracy in large magnetic fields would solve an important problem, for example, in the diagnostics of superconducting magnet systems used for various purposes. There are special efforts to design resistance thermometers for temperature measurements in high magnetic fields [4, 5, 7].

At present, the most commonly used and commercially available cryogenic resistance thermometers are germanium (from 0.05 to 100 K), carbon-glass (from 1.4 to 325 K), metal-oxide (from 70 to 325 K) and platinum (from 14 to 800 K) thermoresistors fabricated as bulk materials, as well as film thermoresistors based on a rhodium-iron alloy (from 1.4 to 325 K), rhutenium oxide (from 0.05 to 40 K) and zirconium oxynitride (Cernox^{TM}) (from 0.3 to 420 K).

A new type of resistance thermometer for measurement of temperatures over the range 0.03 to 500 K can be fabricated using Ge films on GaAs substrates [7-11]. The principles of designing such sensors and the fabrication technology have been reported [8] and the characteristics of different thermometers shown earlier [9-11]. The main advantage of this fabrication technology is the ability to construct thermometers for operation in different temperature ranges, with temperature and field characteristics tailored to meet specific user demands. This is possible by careful control of the technical conditions of Ge film preparation and by the application of modern microelectronic and micromachining technologies to sensor manufacturing.

The subject of this work is the characterization of Ge-film thermometers that can be used in the 0.03 K to 400 K range (models TTR-D [10] and TTR-G [11]). We present: (i) resistance-temperature dependence and sensitivity of sensors in the 0.03 K to 400 K range; (ii) magneto-resistance and temperature error induced by magnetic fields in the 0.5 K to 4.2 K temperature range and magnetic fields up to 9 Tesla; (iii) effect of gamma radiation on sensor characteristics up to doses of 7.6×10^8 rad; and (iv) analysis and computer simulations of the mechanisms of the temperature and magnetic field dependences of the conductivity.

DESCRIPTION OF THE SENSOR

These thermometers are based on Ge film resistors deposited on semi-insulating GaAs substrates using vacuum technology [8]. The sensitive thermometric chips (0.3 mm × 0.3 mm × 0.2 mm) were made using microtechnology and placed in non-magnetic micropackages [11]. The sensor, including micropackge, measures 1.2 mm in diameter by 1.0 mm long. This miniature package protects the sensitive element from harmful external forces.

Some of the microsensors were placed [12] in a second package, a 3 mm diameter by 8.5 mm long copper can, for ease of handling while mounting in a number of cryostats.

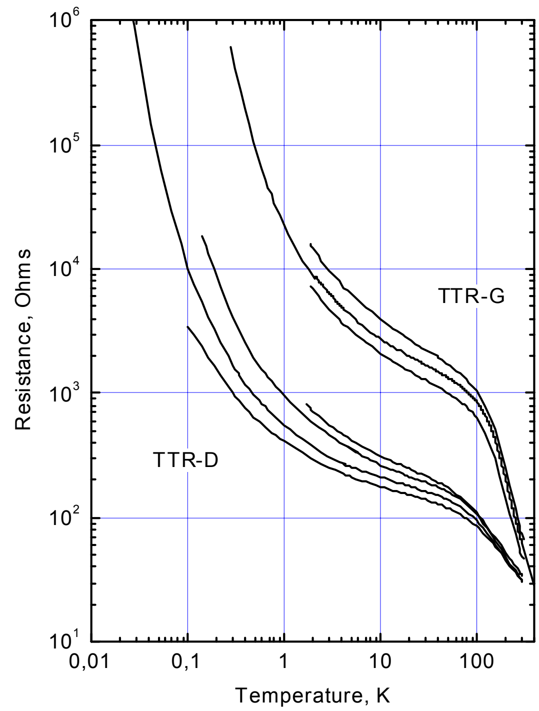
TEMPERATURE DEPENDENCES OF RESISTANCE AND SENSITIVITY

An industrial batch of temperature microsensors has been produced. Shown in Figure 1 are the typical resistance, R, and sensitivity, $|S| = |dR/dT|$, as functions of temperature for two models of thermometers (TTR-D and TTR-G). The TTR-D model can be used in the 0.03 K to 400 K temperature range. The TTR-G model is intended for use in temperature range from 0.3 K to 400 K.

Figure 2 presents temperature dependencies of resistance for a batch of sensors produced from the same Ge/GaAs structure. The variation in thermometric characteristics for different sensors in a batch is related to nonuniformity of Ge films. Nonuniformity of electrical properties of films is due to many technical factors. From a great number of sensors produced using the single Ge/GaAs wafer, it is possible to select groups of sensors with the same thermometric characteristics, which could be interchanged. Usually, from a single Ge/GaAs wafer (30-35 mm in diameter), up to 1500 temperature sensors can be produced with characteristics that meet desired specifications.

BEHAVIOR OF THERMOMETERS IN MAGNETIC FIELDS

The problem of temperature measurement in a high magnetic field is that magneto-resistance in the sensor causes an error in the thermometer reading. The size of this error depends on the material of which the sensor is made, as well as on the sensor design and manufacturing technology. It also depends on the absolute temperature. This is related to the magnetic field effect on the physical mechanisms that are responsible for thermal sensitivity. Therefore, different sensors exhibit different behavior in magnetic field. Behavior of some models of Ge film thermometers in magnetic fields can be found in ref. [9-11, 13].



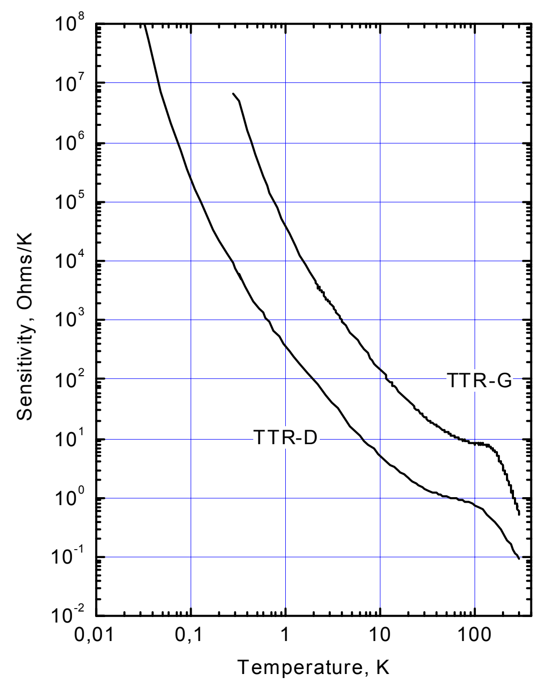


Figure 1. Resistance (upper graph) and sensitivity (lower graph) vs. temperature for Ge-film thermometers models TTR-D and TTR-G

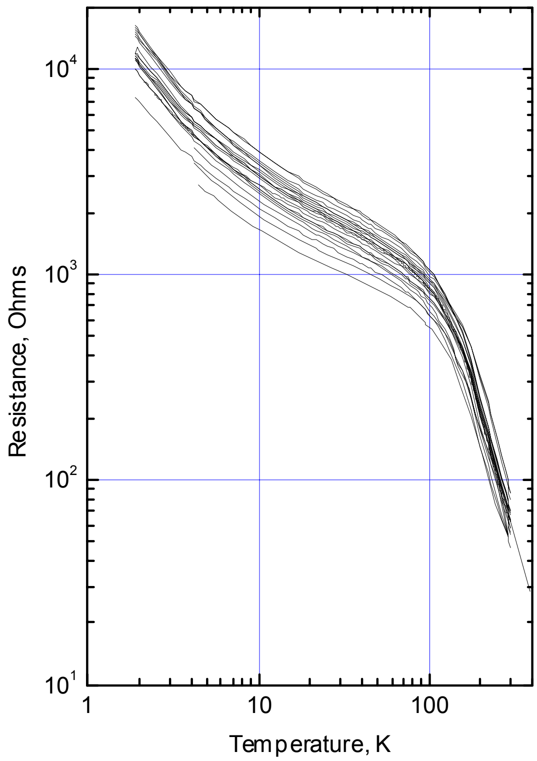
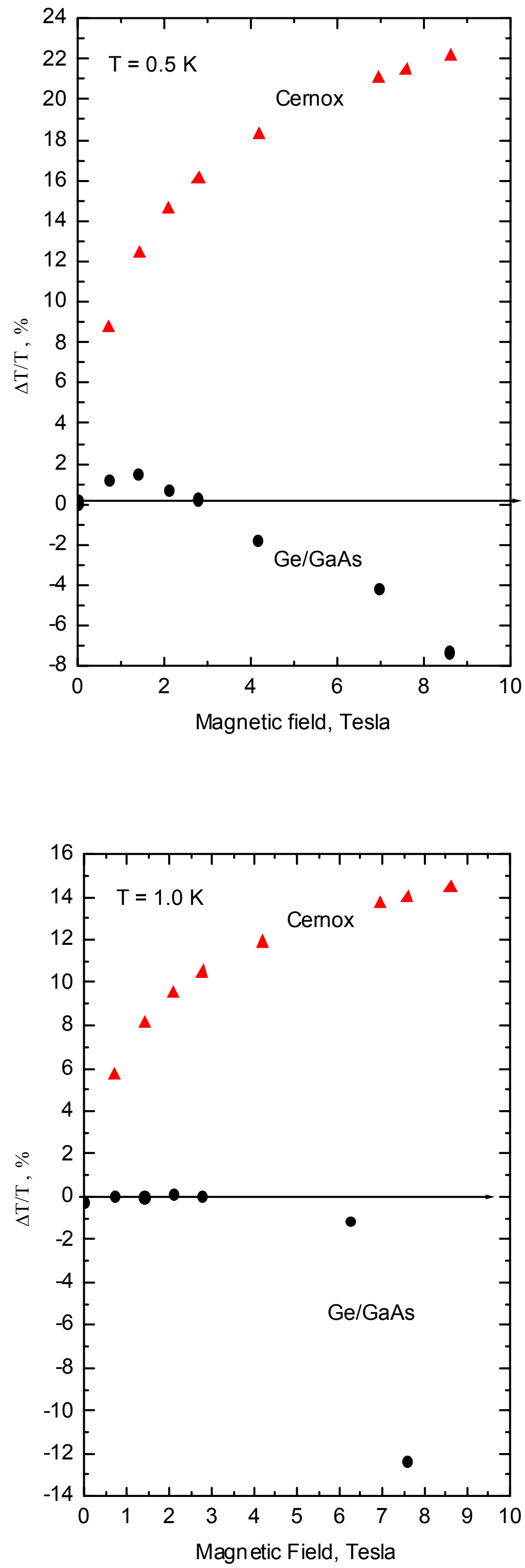


Figure 2. Resistance vs. temperature for a single wafer batch of thermometers



In particular, the effect of magnetic field on the thermometric characteristics of Ge-film sensors depends on the technical conditions of film preparation. By careful choice of fabrication operations, it is possible to make a Ge film with low magneto-resistance and design thermometers for use in a magnetic field environment.

Clearly, an inaccuracy in temperature measurement due to the presence of a magnetic field is an important (albeit negative) characteristic of cryogenic thermometers. The error in the thermometer reading can be given as a ratio $\Delta T/T$, where $\Delta T = T(B) - T$, T is the temperature measured at magnetic field $B = 0$, and $T(B)$ is the temperature indicated at magnetic field B. The magnetic-field-dependent temperature errors, $\Delta T/T$, for the Ge film thermometer at various magnetic fields and temperatures, are displayed in Figure 3. The behavior of zirconium oxynitride (Cernox™) film resistance thermometers produced by Lake Shore Cryotronics Inc. [14] is also shown for comparison.

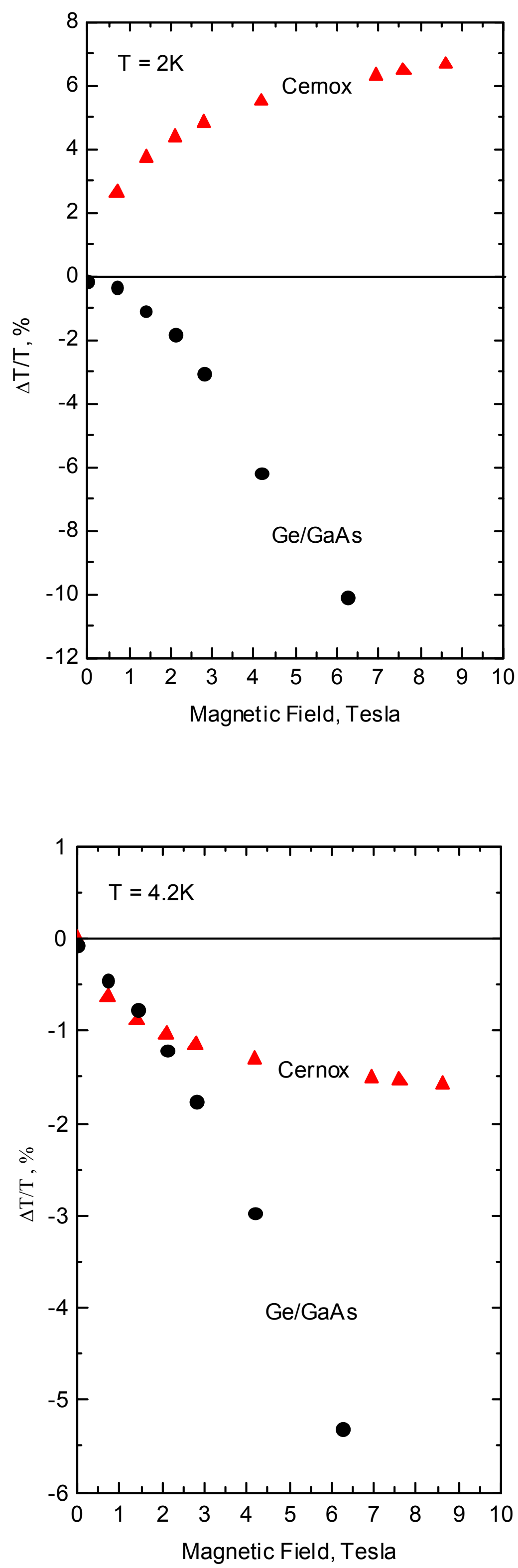


Figure 3. Temperature error Δ*T/T* (in percent) vs. magnetic field at different temperatures for Ge-film and Cernox[TM] thermometers

EFFECT OF GAMMA IRRADIATION

The radiation tolerance of sensors is a very important factor when sensors operate in atomic and nuclear power plants, as well as in various accelerators (such as CERN), which produce high-energy particles, and in space vehicles. In this case, the sensors are exposed to intense ionizing radiation (neutrons and gamma-rays). This fact makes it necessary to study the radiation tolerance of both the materials and sensor designs in order to develop sensors with high radiation tolerance. The effect of irradiation (gamma-ray and neutron) on some models of Ge-film thermometers have been investigated and can be found in ref. [10, 15].

Here we present investigations of the effect of gamma irradiation on TTR-G model thermometers. The gamma irradiation of sensors was carried out at room temperature using ^{60}Co (E = 1.25 MeV) as the source of gamma rays. The temperature in the irradiation zone was about 300-315 K. Shown in Figure 4 is the sensor resistance as a function of gamma-ray dose at 4.22 K. Ge-film microsensors #1 to #8 were treated with gamma radiation. Sensor #9 was not irradiated, but cooled down with the other samples as a control. At T = 4.22 K the sensitivity of sensors is about 1.0 kOhm/K, so that a change of sensor resistance of 1.0 Ohm corresponds to a change in temperature of about 1.0 mK. The main results of irradiation are: (i) the gamma irradiation has very little effect on sensor characteristics up to a dose of 1.5×10^8 rad; (ii) the sensor resistance increases after a dose of 1.5×10^8 rad; and (iii) at the very large dose of 7.6×10^8 rad, an error in the thermometer reading is about 80-100 mK (~2%).

THEORY AND MODELING

The analysis of the experimental data shows that the main mechanism of conductivity is hopping in the regime of Coulomb interactions. The corresponding theory [18] gives a formula for resistivity with exponential accuracy, contains phenomenological parameters, and applies to the localized states far below the mobility edge. Close to the mobility edge, some corrections are necessary, as described below.

We used several theories for the transport in strongly disordered and heavily doped semiconductors, such as the weak localization [16, 17], variable-range hopping [18], and scaling theories of localization [19]. Only the theory of weak localization results in closed, analytic solutions, whereas the other approaches are mostly phenomenological and contain parameters that can not be evaluated theoretically with sufficient accuracy.

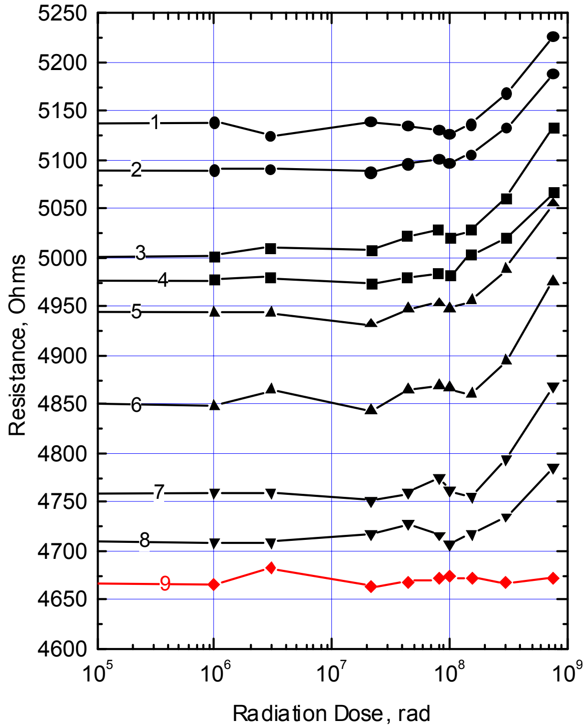


Figure 4. Sensor resistance vs. gamma radiation dose for model TTR-G at 4.22 K

In the framework of variable range hopping, the negative magneto-resistance at low temperature, $T < 0.5$ K, can be attributed to the quantum correction mechanism – suppression of the interference of hopping trajectories by a magnetic field [16]. This explains the dependence of the negative magneto-resistance on temperature (quantum correction increases when the temperature decreases) and also the saturation of magneto-resistance at $H > 1$ T (this magnetic field is strong enough to totally suppress the quantum correction [16]).

For modeling, we use a combination of the scaling theory of localization and variable-range hopping suitable to describe the conductivity and magneto-conductivity close to the mobility edge [13]. In order to estimate phenomenological parameters of the variable-range hopping approach, we used the weak localization theory that contains the information about electronic states above and below the mobility edge. We calculated the mobility edges in the conduction and valence bands of Ge, as a function of the concentration of impurities and magnetic field. To find the position of the mobility edge, we used the weak localization theory. It allows calculating the dependence of the mobility edge on magnetic field $\varepsilon_c(H)$.

This dependence is at the origin of the negative magneto-resistance caused by suppression of the quantum localization correction in a magnetic field. Using the weak localization theory to calculate the mobility edge, we were able to take into account the spin-orbit interaction, originating from the relativistic correction to the scattering from impurities, and also from the spin-orbit terms in the Hamiltonian due to holes in the valence band. At the lowest temperatures, a very small concentration of uncontrolled magnetic impurities can also be important.

It should be noted that at the stage of calculation of the mobility edge position, we can also take into account the corrections from the electron-electron interactions, which are important at temperatures below 1 K. In this way, and also by accounting for the temperature-dependent corrections to the localization corrections, we find the mobility edge dependence on temperature.

To calculate the conductivity, we used the Shklovski-Efros formula for the variable-range hopping below the mobility edge when the Coulomb interaction is present [17]:

$$\sigma(H,T) = \sigma_c \exp\left\{-\left[T_0(H)/T\right]^{1/2}\right\}, \qquad (1)$$

where $T_0(H) = e^2/[a(H)\varepsilon_0 k_B]$, $a(H)$ is the radius of localized state, and ε_0 is the dielectric susceptibility. We assume the radius of the localized state near the mobility edge to be proportional to the localization length L_c: $a(H) = \alpha\ L_c(H)$, where $L_c(H) = l_0[\varepsilon_{c0}/(\varepsilon_c(H) - \varepsilon)]^{\nu}$ depends on electron energy ε in accordance with scaling law, and ν is the scaling exponent of the localization length. The coefficient α is of the order of unity and accounts for a decrease in the radius of localized state at higher magnetic fields. This latter effect is responsible for the positive magneto-resistance in impurity bands (magnetic freezing effect). We take the constants l_0 and ε_{c0} in Eq. (2) equal to the mean free path and the energy of electrons at the mobility edge for H=0. The mobility edge in the scaling region depends on a magnetic field as [20]:

$$\varepsilon_c(H) = \varepsilon_{co}\left[1 - \beta\left(l_0/l_H\right)^{1/\nu}\right], \qquad (2)$$

where $l_H = (\hbar c/eH)^{1/2}$ is the magnetic length. This form is consistent with scaling. In the framework of weak localization theory $\nu = 1$. The coefficient β in the scaling region is of order unity. The important point is that β depends on the spin-orbit interaction. For strong spin-orbit interaction, it changes the sign from positive to negative, which is the source of an anti-localization effect [16]. It can be used to develop thermometers with characteristics independent of magnetic field, even at the lowest temperatures.

The calculated magneto-resistance of p-Ge as a function of magnetic field for different temperatures is shown in Figure 5. Here the concentration of holes is p=4×10^{17} cm^{-3} and the impurity concentration N_i=5×10^{18} cm^{-3}.

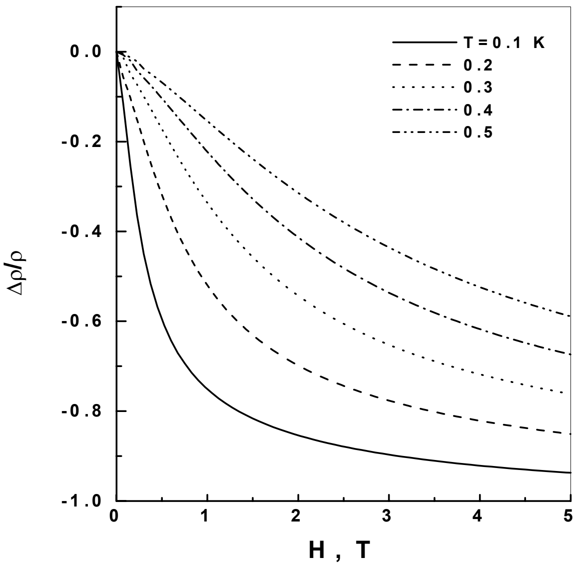


Figure 5. Calculated magneto-resistance of *p*-Ge at different temperatures

The effect of magnetic field is mostly attributed to the suppression of the quantum correction for the hopping trajectories. In our approach it is controlled by varying the position of the mobility edge in a magnetic field. Within the weak localization theory, we also take into account the suppression of localization corrections by the temperature-dependent phase relaxation time [16, 17]. The positive magneto-resistance is also included in our calculations as an effective squeezing of the localization length in a magnetic field. This effect is expected to prevail at higher magnetic fields. Since the negative magneto-resistance is suppressed by temperature, the small positive magneto-resistance dominates at higher temperatures.

The results of calculations are in accordance with experiments. However, some questions concerning magneto-resistance still remain. The experiments show that the negative magneto-resistance prevails only below 0.5 K but the weak localization predicts suppression of quantum corrections at temperatures higher than 0.5 K. A possible explanation is that the effect of temperature on the quantum corrections is stronger near the mobility edge.

CONCLUSIONS

Ge-film thermometers have been produced and investigated in magnetic fields and under gamma irradiation. Their operating temperature regions overlap the 0.03 K to 400 K temperature range. The effect of magnetic field on the thermometers leads to a relatively small magnetic field induced temperature error below magnetic fields of 6 Tesla.

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