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A NEW TYPE OF CURRENT INSTABILITY IN SILICON WITH NANOCLUSTERS OF MANGANESE ATOMS

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ABSTRACT

The current instabilities in silicon with nanoclusters of manganese atoms in accordance with the excitation conditions and the control possibilities for the oscillation parameters discovered by us differ substantially from the current instability found in many other semiconductor materials [1-3]. This is due to the onset of generation of current instability only under illumination by certain wavelengths under the condition of a sufficiently low IR light intensity, as well as a pronounced dependence of the current frequency on the energy of the incident photons. It should be noted that such instabilities of current are observed only in silicon samples with nanoclusters of manganese atoms, and in the samples with analogous electrophysical parameters, manganese-doped without the formation of clusters, the effect is absent.

Key words: instabilities, silicon, atom, condition.

Unlike other elements of transition groups, manganese atoms under certain thermodynamic conditions are formed into nanoclusters near the boron ion due to the process of self-organization. The formation of nanoclusters comprising four manganese atoms located in the nearest equivalent interstitial positions in the negative boron ion is confirmed by the EPR and AFM methods. [4-5]. Clusters with clusters have lines of the EPR spectrum associated specifically with nanoclusters of four manganese atoms and consisting of a finely divided 21 Line. The so-called "low-temperature diffusion technology" of doping developed by us [6-7] made it possible to ensure the maximum participation of manganese atoms introduced in the formation of clusters. As the starting material, single-crystal *p*-type silicon doped with boron was used, with a resistivity of ~ 3 Ohm-cm.

Was made of 10 highly compensated samples *p*-type with resistivity $\rho \sim 5 \cdot 10^3 \div 7 \cdot 10^3$ Ohm-cm at $T=300$ K and practically the same geometrical parameters ($8 \times 3 \times 0.7$ mm³). To verify that the observed phenomenon is associated with bulk properties of the material after diffusion doping, the samples were polished on all sides to a depth of ~ 50 μ m. Surface treatment of the samples (polishing or grinding) has virtually no effect on the condition of the excitation and parameters of the instability of the current. Ohmic contact was created by applying Nickel coating on the ends of the sample of size 3×0.7 mm².

The instability of current was studied on the installation (figure 1), equipped with a special cryostat, pozvol'yayuschimi temperature, the magnitude of the electric field in the sample and the power of the incident izlucheniya a wide interval of values. Lighting the top surface of the samples (8×2 cm²)

monochromatic infrared radiation was carried out using prismatic IR monochromator. To avoid the exposure incident on the sample scattered and stray light with a photon energy of $h\nu = E_g$ used filter of polished silicon, which was mounted in the window of the cryostat.

Self-oscillations of the current were recorded using the instrument UT81B in real-time when connecting to a personal computer. During the measurement, digital oscilloscope, multimeter UT81B were connected in the measurement mode current, we can therefore neglect the redistribution of the applied voltage between the sample and input resistance of the measuring device.

The kinetics of excitation of current instability was also measured using the load resistance $R_1 = 1000 \Omega$, the value of which is substantially smaller than the resistance of the sample $R_{\text{samp}} \sim 10^{10} \Omega$ at $T = 100 \text{ K}$.

In research of self-oscillations of the radiation power at various lengths was volodarevych on one level – $W \sim 10^{-5} \text{ W}$. The value of the power of the incident IR radiation is changed by using calibrated metal grids, which are mechanically lowered between the cryostat window and the exit slit of the spectrometer.

It is established that current-voltage characteristic (CVC) of the samples in the absence of IR radiation at 300 K was linear, and at $T = 200 \text{ K}$ consisted of three distinct sections: in the region of low electric field $E = 0,1 \div 10 \text{ V/cm}$ – ohmic, at $E = 10 \div 50 \text{ V/cm}$ – squared, and if $E > 160 \text{ V/cm}$, the current is quickly increased, and the dependence of the current on the voltage in this area is described by a power law with pokazatelem stepeni $\sim 3 \div 6$. At higher electric fields the CVC again represented by a quadratic law. Based on these results it can be concluded that in the samples there are signs of monopolar injection [8, 12], and when $E > 160 \text{ V/cm}$, the full filling of traps (PEPS). However, no current oscillation was not observed. Under the same conditions, the samples were investigated in the presence of infrared radiation in the region $h\nu = 0,12 \div 0,45 \text{ eV}$, while the CVC remains the same, but there is a start offset quadratic phase PEP in the low side voltages, which is a significant increase of the photocurrent. When atomic level region of the electric field, the instability of current was not detected.

Figure 3 shows the change of photocurrent with time in the samples at lower temperatures ($T = 100 \text{ K}$), $E = 200 \text{ V/cm}$ and the IR illumination radiation with a photon energy $h\nu = 0,12 \div 0,45 \text{ eV}$. Found that regardless of electrophysical parameters of the sample, temperature and electric field, the maximum threshold energy of the photon, wherein the excited instability current is $h\nu = 0,42 \text{ eV}$ ($\lambda \sim 3 \mu\text{m}$). As can be seen from the figure, the instability of current in this case have the form of oscillations of the relaxation type, the current value gradually increases with time and then the current abruptly increases by $1 \div 1,5$ m order, followed by a sudden drop of current by $1,5 \div 2$ orders of magnitude (figure 3,b). The oscillation frequency is stable in time and is $f_{os} = 4,32 \cdot 10^{-2} \text{ Hz}$, i.e. observed for infralow-frequency fluctuations with an amplitude of about 10 mA, with a modulation index $M \sim 96 \%$.

Amenities photon energy of the infrared radiation incident on the sample, the shape of the current oscillations is retained completely, the oscillation frequency

considerably decreases and the amplitude increases and, accordingly, the modulation depth also increases to almost 100%.

The lower limit of photon energy in which observed oscillations is $h\nu=0.12$ eV ($\lambda\approx 10$ μm), the oscillation frequency is $\nu_{os}=1.18\cdot 10^{-3}$ Hz, the amplitude is about 25 – 30 mA (figure 3, h). At constant temperature and electric field parameters and the shape of the oscillations is quite stable and not changing. Found that under illumination of the samples with $h\nu<0,12$ eV, regardless of the value of the electric field current oscillations are not excited. Thus, the excitation of the instability current is only in the range of wavelengths of IR radiation $\lambda=3\div 10$ microns.

It is established that under the same external conditions, the instability current is also observed in compensated samples *p*-type with higher resistivity (ρ to $1\cdot 10^4$ Ohm·cm at $T=300$ K).

As far as we know [2-7], in silicon doped to different impurity atoms *otsutstvuyutpredmetu* in the area we studied temperature and photon energy. Therefore, we can assume that the existence of the instability of current-driven infrared light with $\lambda=3\div 10$ μm , indicating a significant difference of physical processes in silicon nanoclusters of manganese atoms from the other processes in semiconductor materials. It should be noted that the frequency of the current oscillations is very sensitive to photon energy (figure 3).

When you change the energy of incident photons in the range $h\nu=0.12\div 0.43$ eV, the oscillation frequency increases more than 20 times, and according to a linear law:

$$f=f_0+k\Delta h\nu$$

Where: f_0 – the frequency at $h\nu_0=0.12$ eV, $\Delta h\nu=h\nu-h\nu_0$, $k=0.13$ Hz/eV.

Studies have shown that the temperature region of existence of the instability current value depends on the applied electric field and the energy of incident photons (figure 4). With the increasing intensity of the applied electric field and temperature region of existence of oscillations expands mainly in the direction of high temperatures. With increasing energy of the photons it narrows off to the side of low temperatures. If we change the value of the electric field in the range $E=100\div 300$ V/cm, the upper limit of the temperature at which oscillations changes from $T=130$ K to $T=140$ K.

Found that the constancy of the photon energy and electric field dependence of oscillation frequency on temperature is described by the law:

$$f=f_0+K(T-77)$$

Where: f_0 is the frequency at 77 K, T is the absolute temperature, $K=2.4\cdot 10^{-4}$ Hz/K is the oscillation Amplitude of the temperature changes very little.

The threshold electric field at which you start to get excited current oscillations in a, $E\sim 100$ V/cm. Changes of parameters of self-oscillations under different electric fields is shown in figure 5. With increasing electric field, the shape of the oscillation remains stable and the frequency varies with the coefficient $A=0.13\cdot 10^{-3}$ Hz/V.

Studies have been conducted of the parameters of the instabilities of the power of the infrared radiation of paduasoy sample, the maximum power was

$10 \cdot 10^{-6}$ W. With a reduction of the amount of power the period of oscillations increases and the oscillations disappear with a radiation power of less than $0.5 \cdot 10^{-6}$ W (figure 6).

The obtained experimental results allow to identify the following features of the instability current in the silicon nanoclusters of manganese atoms:

1. Vibrations are produced only in a fairly wide region of the IR spectrum of $h\nu=0.12 \div 0.43$ eV, where the only possible impurity photoconductivity.

2. The oscillation frequency is very low and lies in the range $f_{os} = 4.3 \cdot 10^{-2} \div 1.98 \cdot 10^{-3}$ Hz.

3. The oscillation frequency is strongly dependent on photon energy and this dependence is linear with the proportionality coefficient $G \sim 2.4 \cdot 10^{-4}$ Hz/K.

4. Despite the low power pausegame, obrazec radiation ($W=10^{-5}$ W), and the amplitude is quite high at 25 – 30 mA.

5. Fluctuations are observed in the samples ot delnym resistance more $\rho=3 \cdot 10^3$ $\Omega \cdot \text{cm}$, regardless of their size and surface treatment (polishing, grinding).

6. The shape of the oscillations depends weakly on the energy of incident photons, temperature and electric field.

The results obtained are difficult to explain recharging of energy levels of isolated atoms of manganese in silicon. This is due, firstly, to the fact that the energy levels of atoms of manganese ($E_1=E_C-0.27$ eV, $E_2=E_C-0.5$ eV) [14] in the studied samples are almost completely exempt from electrons, since the samples have *p*-type conductivity with the Fermi level position $F=E_V+0,35$ eV.

Second, the photoconductivity in the region $h\nu=0,12 - 0,4$ eV, koterayama associated with the transition of electrons from the valence band on the energy levels lying in the energy interval $\Delta E=E_V-(0,12 - 0,43)$ eV, stimulates the excitation of current oscillations. These levels are not associated with the energy levels of isolated atoms of manganese.

Therefore, we can assume that the formation of nanoclusters (quantum dots) consisting of four atoms of manganese, there is a rearrangement of the energy levels of electrons due to the overlap of the *s* – electron shells of atoms in the nanocluster. It is also possible change the position of the energy levels in a quantum dot, depending on the charge state of the cluster, which appear mini energy bands in the energy interval $\Delta E=0.12 - 0.43$ eV.

Thus, the formation of multiply charged clusters of the manganese atoms, i.e. quantum dots, there is a significant restructuring of the energy levels of electrons, which not only causes the emergence of a number of new effects such as a substantial extension of the spectral region of photosensitivity of silicon and abnormally high impurity photoconductivity [13], but also triggers the generation for infralow-frequency fluctuations in current. Parameters of self-oscillations depend tenelia incident photons (in the range of $h\nu=0.12 - 0.4$ eV), in addition, a significant dependence of the oscillation frequency of the wavelength of the IR radiation shows the possibility of creating a new class of photodetectors, working in the field $\lambda=3 - 10$ μm with a frequency output. All these data show that silicon nanoclusters of manganese atoms is a unique photovoltaic material and require

more detailed theoretical and experimental study.

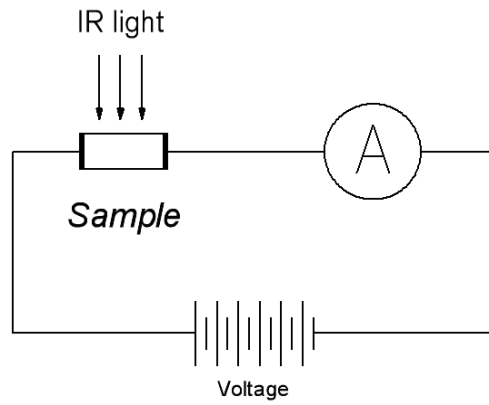


Fig.1. The scheme of measurement with a direct connection.

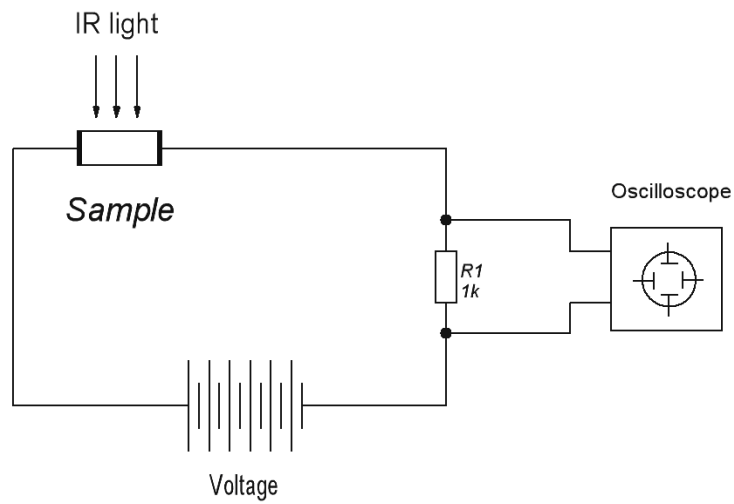
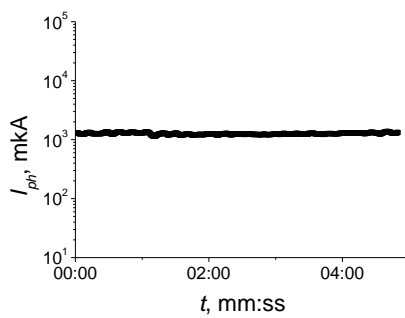
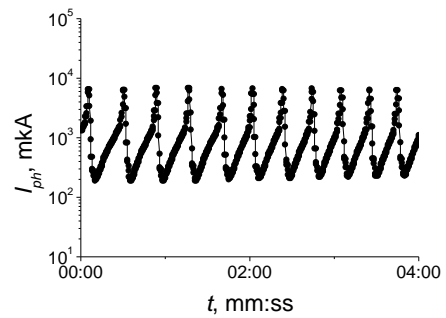


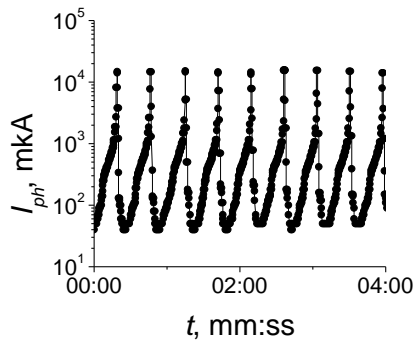
Fig. 2. Current measurement scheme with low load resistance.



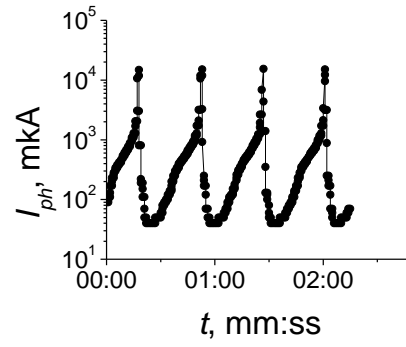
a) $h\nu=0.45$ eV.



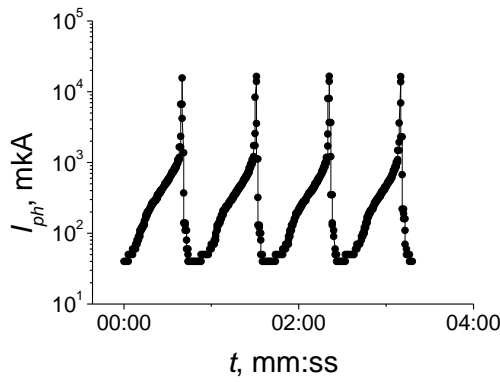
b) $h\nu=0.43$ eV; $T= 23$ sec.



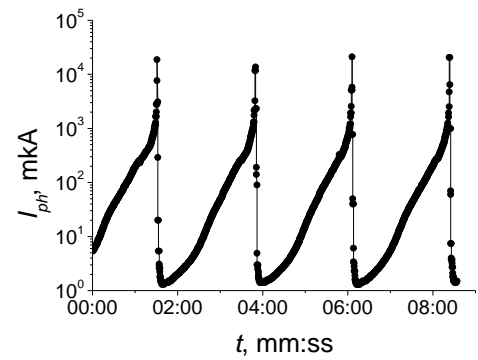
c) $h\nu=0.35$ eV; $T=28$ sec.



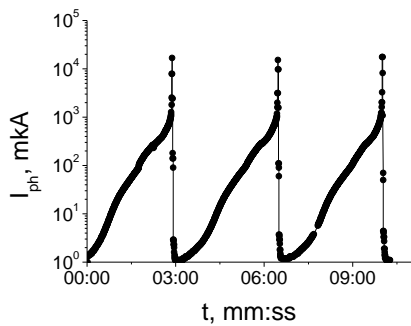
d) $h\nu=0,3$ eV; $T=35$ sec.



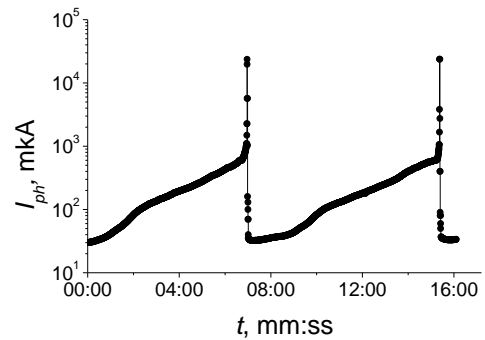
e) $h\nu=0.23$ eV; $T=51$ sec.



f) $h\nu=0,16$ eV; $T=138$ sec.

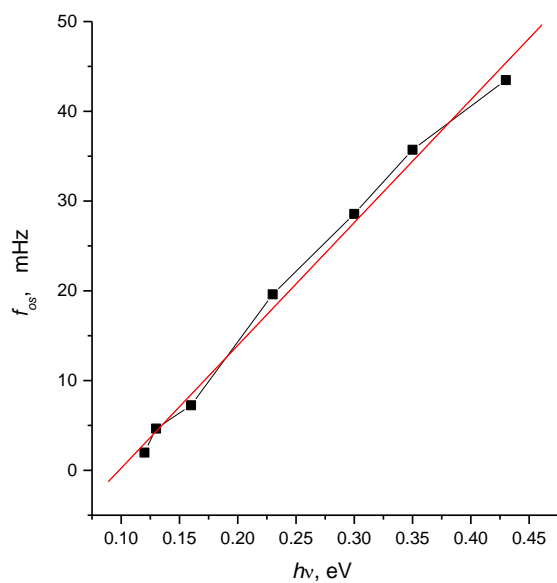
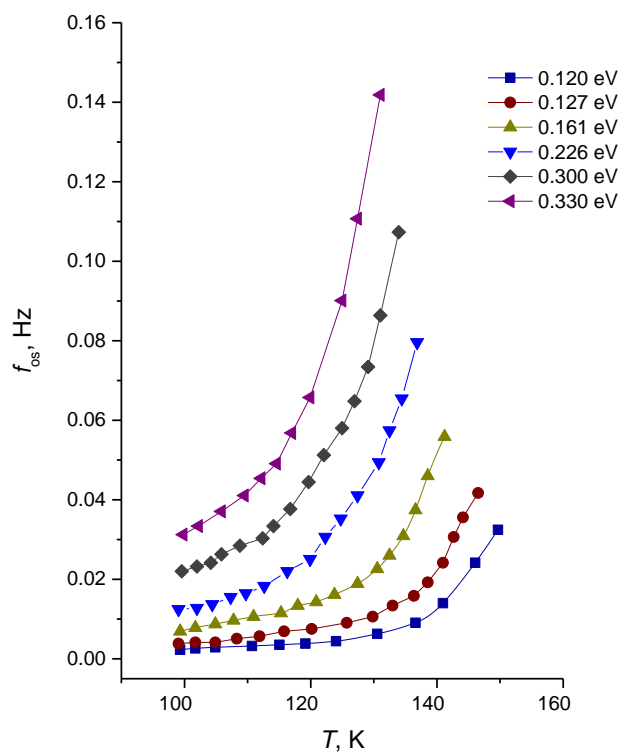


g) $h\nu=0,13$ eV; $T=215$ sec.



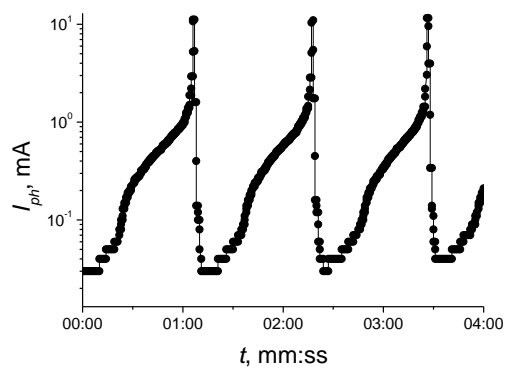
h) $h\nu=0,12$ eV; $T=505$ sec.

Fig. 3. Changes in the parameters of current oscillations with a change in photon energy,
 $T = 100$ K.

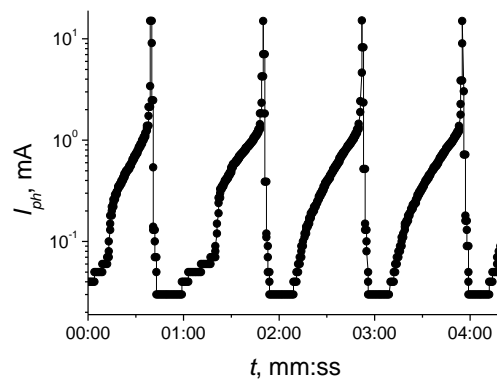


$$\frac{f_{os}}{h\nu} \propto 0,136 \frac{\text{Hz}}{\text{eV}}$$

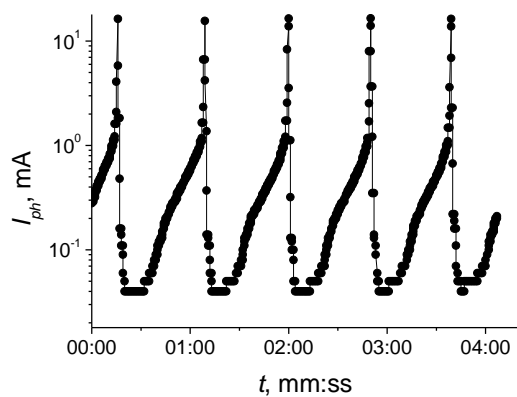
Fig.4. The change in the oscillation frequency as a function of the energy of the incident photons at $U = 250$ V, $T = 100$ K.



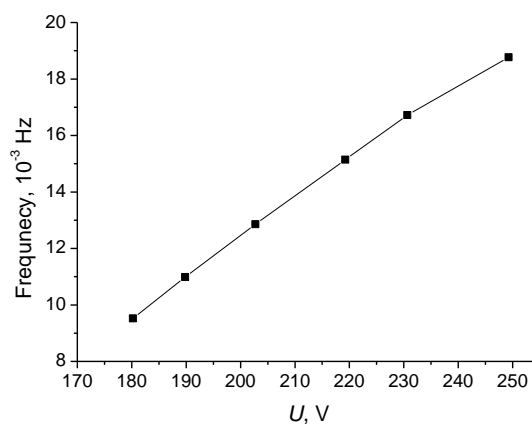
a) $U=180$ V; $T=105$ sec.



b) $U=225$ V; $T=63$ sec.



c) $U=250$ V; $T=53$ sec.



$$d) \frac{f_{os}}{U} \propto 1.3 \cdot 10^{-4} \frac{\text{Hz}}{\text{V}}$$

Fig. 5. Changes of current oscillation parameters for various electric fields, $h\nu=0,226$ eV, $T=100$ K.

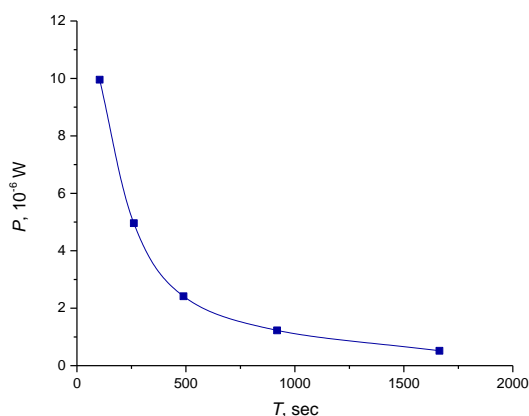


Fig. 6. Dependence of the period of current oscillations on the power IR radiation incident on the sample.

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