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The formation of chondrule-like particles in RF discharge plasma

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Chondrules are fundamental components of chondritic meteorites and play a vital role in understanding the formation of the early solar system. This study focuses on the synthesis of chondrule-like particles in a plasma environment using a radiofrequency (RF) discharge. The experimental setup involves a vacuum chamber where argon gas, hexamethyldisiloxane (HMDSO), and ferrocene vapors are introduced. The plasma burning duration is optimized to facilitate chondrule formation, followed by analysis of the synthesized particles using scanning electron microscopy (SEM) and energy dispersive analysis. The results demonstrate the successful synthesis of chondrule-like particles with diverse sizes and morphologies. SEM imaging reveals particles ranging from 80 to 378 nm in diameter, exhibiting rounded and non-uniform shapes. Energy dispersive analysis confirms the presence of iron, carbon, oxygen, and silicon in the synthesized particles. Iron and carbon originate from the ferrocene and HMDSO precursors, respectively, while oxygen may indicate oxidation or the presence of oxide groups. Silicon, the main component, contributes to the key characteristics of the chondrule-like structures. These findings contribute to the understanding of chondrule formation mechanisms and pave the way for further investigations using combined discharges to simulate shock waves or nebular lightning. Additionally, the study suggests the possibility of introducing additional chondrule building blocks, such as magnesium and phosphorus, to explore their effects on particle synthesis and composition.

Key words: plasma, RF discharge, chondrule-like particles.
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1 Introduction

Chondrules are the main structural components of chondritic meteorites, the oldest meteorites in the solar system and the most common variety of stony meteorites found on Earth. They are ferromagnesian silicate-rich spherules, average diameters of which vary from 0.02 to 1 mm [1, 2]. Depending on the classification of chondrites, chondrules occupy approximately 20 to 80 percent of the chondrite's volume (with the exception of CI-chondrites since they do not contain chondrules) which makes them the dominant component in chondrites [2]. Judging by their abundance and their chemical composition which is similar to that of the solar photosphere (with the exception of some elements) [3], it could be concluded that they were common components in the early solar system. Thus, closely investigating the complex chemical composition of chondrules and identifying the mechanisms of their formation can provide a deeper understanding of the formation of the solar system.

The exact mechanisms of chondrule formation and their precursors have not been established and have been the subject of discussion for more than a century. However, their chemical composition and properties such as melting point and cooling rate impose certain constraints on the mechanisms of their formation and the conditions of the environment in which they were formed, which suggests what processes could possibly occur in the environment of the protoplanetary disk [4, 5]. Alexander et al., based on the chemical composition of chondrules which includes volatile elements, concluded that there might be regions of nebula with a much higher solids density than expected previously, and this insight might also help to understand the mechanisms of planetesimal formation [6]. Based on the thermal history of chondrules which suggests that they were formed as a result of a flash heating of silicate particles with a rapid cooling afterwards, various possible processes that could provide the conditions necessary for the formation of chondrules have been proposed. One of the most favored mechanisms of chondrule formation is a nebular shock wave which corresponds to chondrules' thermal histories [7-12]. Other mechanisms include formation of chondrules by collisions of planetesimals [13, 14] and nebular lightning [15-17].

So far, numerous experiments have been conducted in order to obtain chondrule analogues using an approximate reconstruction of some of the proposed mechanisms under both terrestrial and microgravity conditions [18-22]. To gain insight into the formation of chondrules by nebular lightning, Spahr et al. subjected micron-sized particles of forsterite, a component widely found in natural chondrules, to arc discharges in a special chamber aboard the International Space Station (ISS) and compared the acquired aggregates with the ones obtained on Earth [20-22]. Morlok et al. investigated the formation of chondrule analogues using hot plasma to simulate the formation of chondrules resulting from flash heating by a nebular shock wave [23].

In these experiments [18-23], crushed terrestrial minerals and their mixtures were used as the precursors to obtain chondrule analogues. It can be assumed that silicate particles formed in dusty plasma can also be used as a starting material for chondrule-like objects. Currently, the investigation of the emergence and growth of dust particles in a 13,56 MHz radio-frequency (RF) discharge plasma, sustained in a mixture of argon and hexamthyldisiloxane (Ar-HMDSO) with HMDSO being the molecular precursor, is being carried out [24-26]. Based on the formation of particles in a dusty plasma, the mechanisms of cosmic dust formation and the synthesis of its analogues in laboratory conditions are being investigated [27].

Thus, the synthesis and study of the growth mechanism of chondrule-like particles in a plasma medium is an urgent task for understanding the processes of formation of the Solar System, since more than 90 percent of the baryonic matter in outer space consists of plasma, which in turn imposes certain conditions in the formation of such particles. In this work, we consider the results of experimental work in argon plasma with the introduction of HMDSO and ferrocene vapors for the synthesis of chondrule-like particles. At the first stages of the study, it is planned to carry out the growth of chondrule-like particles in the plasma of a radio-frequency discharge. In the future, combined discharge will be used to simulate shock waves or lightning due to spark discharge, ultraviolet radiation or other types of influence.

2 Experimental part

In this work, chondrule-like particles were synthesized in a plasma environment using a radiofrequency (RF) discharge at low pressure. An experimental setup is presented in Fig. 1. It consists of a vacuum chamber with an electrode system for plasma generation, as well as a system for feeding gases (argon) and vapors (hexamethyldisiloxane (HMDSO) and ferrocene).

The synthesis of chondrule-like particles occurs in the following procedure. Before the experiment, air is removed from the vacuum chamber by a combination of mechanical and turbomolecular pumps until a residual pressure of about 10^(-5) torr is reached. After achieving the required vacuum in the chamber, the inert gas argon with the specified flow rate of 120 sccm is fed into the system. Ferrocene and HMDSO vapors are also introduced into the working chamber, where the decomposition reaction and the formation of chondrule-like structures take place. A needle flow meter (Edwards) and a gas mass flow controller (Bronkhorst) are used to control and maintain the stability of the gas flows. These gauges provide accurate control and measurement of the flow rate of the gas components in the system. A 13.56 MHz radio-frequency power supply connected to an electrode system generates an electric field that ignites plasma inside the chamber. The plasma contains charged particles that collide with ferrocene and HMDSO vapor molecules, causing decomposition and the formation of tiny silicon particles.

The plasma burning duration is optimized to achieve maximum formation of chondrule-like particles. The plasma is ignited for 30 seconds, providing sufficient time for reaction and particle formation, and then turned off for 60 seconds to allow the particles to settle on the substrate. This cycle is repeated 20 times to obtain a significant quantity of particles for further studies.

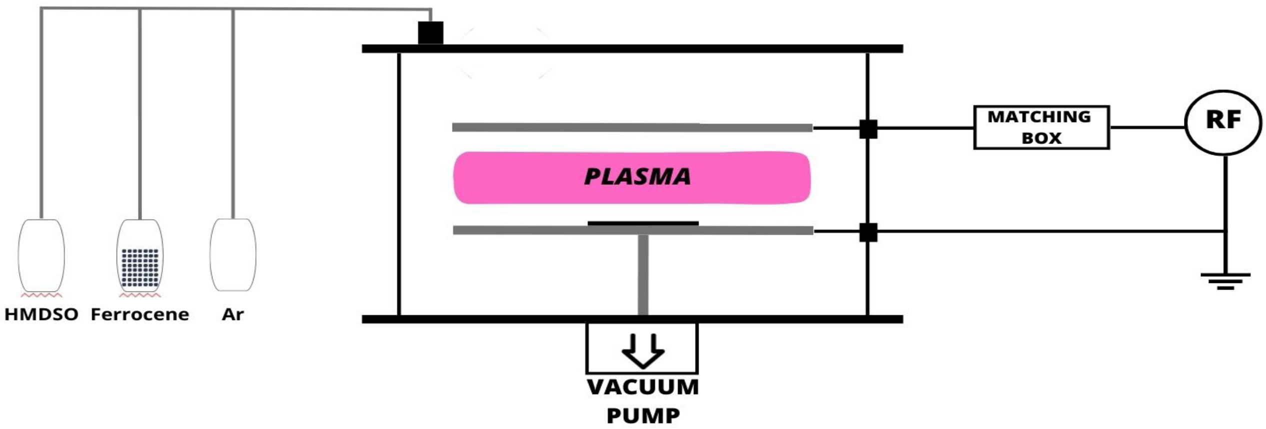


Figure 1 – PW-7 coaxial plasma accelerator

After the synthesis of chondrule-like particles is completed, further analysis of the obtained samples takes place. Electron microscopy was used to study the size, shape and morphology of the particles. The elemental composition of the obtained particles was analyzed by energy dispersive analysis to determine the presence and concentration of chemical elements.

3 Results and Discussion

The experimental results showed the efficient synthesis of chondrule-like particles in the plasma environment using the experimental setup described above. The major results of the study are the morphology and size of the formed particles.

Basically, the combinations of Ar/HMDSO+Ferrocen vapor and inert gas in the RF discharge allow the synthesis of chondrule-like nanoparticles, which can be seen in the scanning electron microscopy (SEM) images. According to the experimental observations, the size of the obtained nanoparticles was found to strongly depend on the plasma parameters, such as the discharge power, gas pressure, flow velocity, plasma temperature, etc. Nevertheless, in this work we focused on the study of the morphological and structural properties at certain optimal plasma parameters.

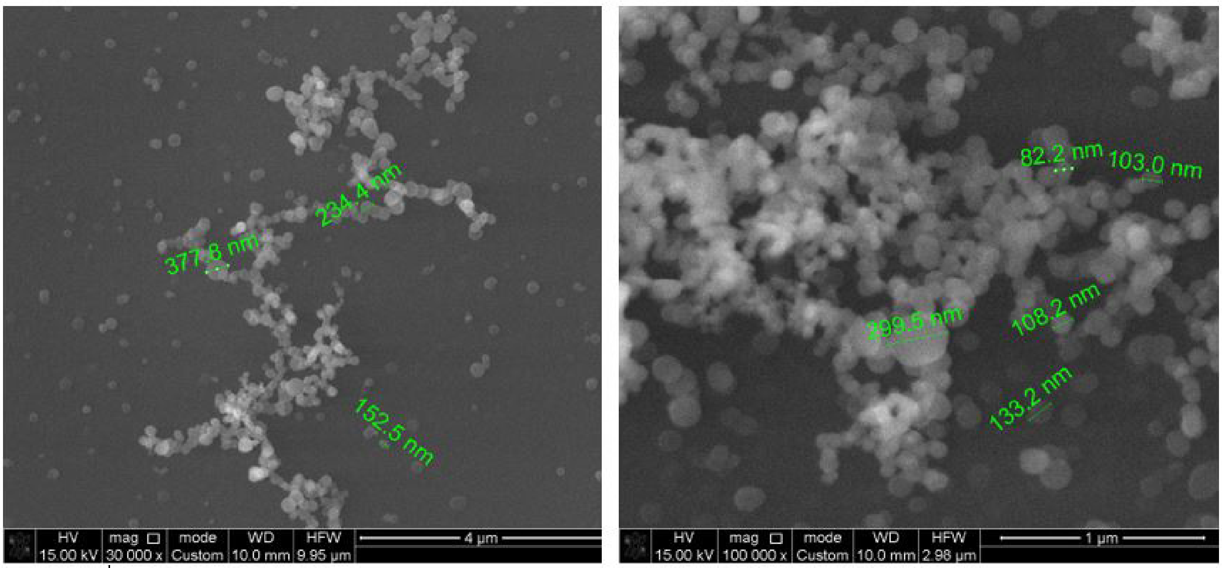
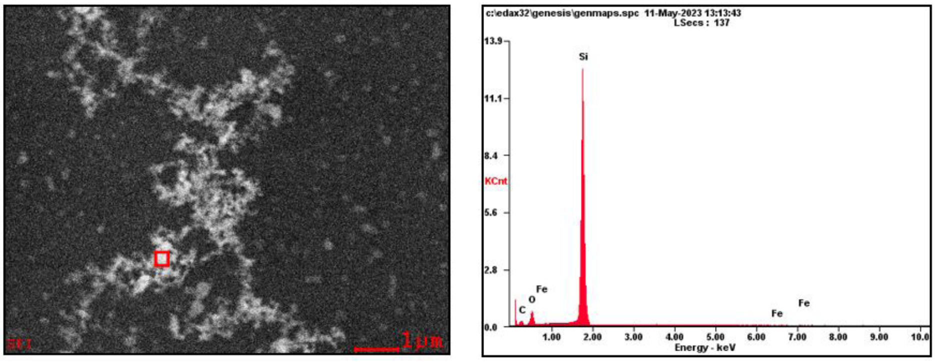


Figure 2 – SEM imaging of formation

On the basis of SEM images, it was found that the synthesized chondrule-like particles had a variety of sizes. Particles ranging up to several tens of nanometers in diameter (from 80 to 378 nm) were observed. In addition, a variety of particle shapes were found. Particles with rounded and non-uniform shapes were observed as a result of the reaction in the plasma medium. This indicates different processes of particle formation and growth, which may depend on the reaction conditions, concentration of starting materials, and other factors.

Energy dispersive analysis of the synthesized chondrule-like particles revealed the presence of several constituent elements. In particular, the following elements were found: iron (Fe), carbon (C), oxygen (O) and silicon (Si). The presence of iron (Fe) can be attributed to the use of ferrocene as a starting material. Ferrocene contains iron atoms, which can become part of the synthesized particles. Carbon (C) may be present in the particle composition due to the use of hexamethyldisiloxane (HMDSO) as a starting material. HMDSO contains carbon atoms, which can also be included in the structure of the synthesized particles. Oxygen (O) may also be present in the particle composition, possibly related to oxidation or the presence of oxide groups on the particle surface. In addition, the main element found in the synthesized particles is silicon (Si). Silicon is the main building block of the chondrule-like structure and provides its key characteristics.



Element	Wt%	At%
CK	16.97	30.18
OK	11.87	15.85
SiK	70.76	53.82
FeK	0.40	0.15
Matrix	Correction	ZAF

Figure 3 – Chemical composition

Thus, the results of the elemental composition analysis allow us to establish that the synthesized chondrule-like particles contain different elements, such as iron (Fe), carbon (C), oxygen (O) and silicon (Si). This confirms the complex chemical composition of the studied particles, which is important for further understanding of their structure and properties.

4 Conclusions

In conclusion, an experiment on the synthesis of chondrule-like particles in plasma medium using a radio-frequency discharge at low pressure showed the successful formation of particles with a variety of sizes and morphologies. Using a combination of hexamethyldisiloxane (HMDSO) and ferrocene vapor in a plasma environment resulted in the formation of – chondrule-like structures containing iron (Fe), carbon (C), oxygen (O) and silicon (Si).

Thus, the experimental results confirm the successful synthesis of chondrule-like particles with a variety of morphology and sizes, as well as indicate their complex chemical composition. This opens up opportunities for further research using, as previously mentioned, the combined discharge to simulate shock waves or nebular lightning and the introduction of additional chondral building blocks like magnesium, phosphorus and other elements.

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