Rod-Like Particles in Gas Discharge

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In most of experiments on strongly coupled complex (dusty) plasma spherical particles are used. In the present work the levitation and ordering of very long rod-like particles – needles (length-to-radius ratio is 40-80) suspended in striations of a dc discharge or in the sheath of a rf discharge is reported and analyzed.

The dc glow discharge with cold electrodes was created in a vertically positioned glass tube of 3 cm inner diameter. Electrodes were maintained in the lateral nibs and separated by 40 cm. The tube was filled with neon or neon-hydrogen mixture up to the pressure 0.1 – 2 torr. The discharge current varied in the range from 0.1 to 10 mA. Regimes with standing striations existed in this range of parameters. Dust particles to be introduced into the plasma were held in the container with a grid bottom above the upper electrode (anode). As the container was shaken the particles rained down into the column of the discharge. Particles were illuminated with the laser beam formed into a converging sheet with the aid of cylindrical lenses. Scattered light was observed by a CCD video camera. To provide the levitation of nylon macroparticles ($\rho = 1.1$ g/cm^3) of diameter 15 μm and length 300 μm, and diameter 10 μm and length 600 μm a neon-hydrogen mixture was used. These dust grains formed the structures, consisting of 3-4 horizontal layers. Lighter particles (diameter 7.5 and 10 μm, length 300 μm) levitated in neon striations and formed much more axially prolonged structures.

The structures formed of microcylinders indicated a pronounced short-range order. All the particles lied in the horizontal plane and all aligned in the certain direction. *A priori* these particles were supposed to follow the cylindrical symmetry of the discharge. However, the orientation of the particles is not connected with the discharge symmetry. The preferential direction is not also the result of interaction between the particles, because single particles are oriented in the same direction as the particles in the structure. Furthermore, very strong interaction between single micro-rods floating in the discharge when they are separated by the distance about only 50 μm does not significantly change their orientation. The charge on the dust particles estimated from the levitation condition is assumed to be about $8 \cdot 10^5$ electrons and so huge quadrupole moments are expected there.

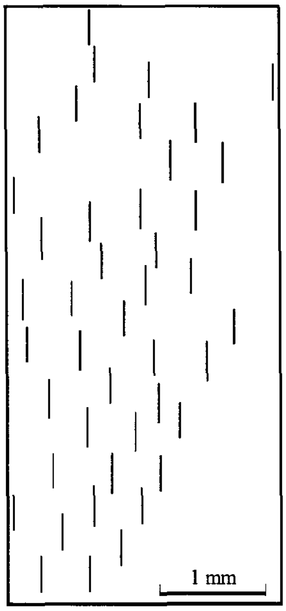

Fig.1. Digitized image of horizontal section of a structure formed of grains 300 μm long and 15 μm in diameter in dc discharge

The preferential direction of the particle orientation in the horizontal plane seems to originate from the slight constructional asymmetry of the discharge tube. To verify this supposition an asymmetrical distortion was introduced into the discharge. A dielectric plate with a hole placed several centimeters above the cathode induced it. The plate overlapped the discharge section so that the formation of the column started through the hole with the diameter of 1 cm. The visually observed distortion of the standing striation indicated the presence of the axially asymmetric part of the electric field. The turning of the plate resulted in the change of the orientation of parlcles.

In the subsequent experiments microcylinders of diameter 10μm and length 300 and 600 μm coated with a thin layer of a conducting polymer (polypyrrole) were used. In dc discharge these particles behaved in the same way and formed structures of the same shape as the micro-rods of the same sizes without coating.

The rf experiments are performed in GEC cell filled with krypton or argon. A ring of 0.5 mm thickness and 25 mm internal diameter is placed on the lower driven electrode in order to create a shallow electrostatic well for the levitating needles. The same particles as in the dc discharge were used.Levitation of needles is observed on the edge of the collisional rf sheath. Longer rods float horizontally mainly in the center of the area enclosed by the ring, while the shorter rods settle vertically around, parallel to the strong electric field of the sheath. Usually rods with some inclinations spin about vertical axis. The horizontal rods float near the top of the vertical ensemble in the central region and near the bottom in the vicinity of the ring. Levitation of the rods is only possible for the discharge pressure above 5 Pa and power greater than about 20 W. Further increase in the power neither increases significantly the bias voltage nor affects noticeably the grain levitation (whereas the discharge rf current gows). Another critical parameter is the amount of the injected powder: The average interparticle distance for very few vertical rods is about 1 mm; by introducing more powder the interparticle distance decreases to about 0.3 mm without losing of the hexagonal structure. When a few more needles is introduced the overall crystal quality degrade with a clear increase of the particle kinetic energy. It is not possible to levitate the needles at higher densities, the excess particles just fall through. Levitation of particles covered by conducting polymer is practically impossible at the conditions when dielectric particles with the same other characteristics are suspended. Instead these conductive particles stuck to the electrode with the orientation close to vertical.

The main experimental features fit well with a model developed that includes parabolic profile for the sheath electric field and assumption that ion flux to a cylindrical rod is radial. Estimations of the rod charge, induced dipole and quadrupole moments were fulfilled. Preferable orientation of rods is determined by the competition between interaction of the inhomogeneous electric field of the striation or sheath with the induced dipole and the quadrupole moments of the needle. The interaction wih the quadrupole prevails in the case of large particles. This can explain the horizontal orientation of such particles. With decrease of size the dipole part of interaction becomes more important and hence the shorter particles levitate vertically. In dcdischarge the particle charge is usually higher than in rf discharge. As result, the electric field in the region of the particle levitation is smaller and, in spite of decreasing of the electric field gradient, the interaction with quadrupole prevails. I is a possible reason of the horizontal levitation of rod-like particles in striations of the dc discharge.

Preliminarily results were published in [1,2].

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1. V.I. Molotkov, A.P. Nefedov, M.Y. Pustyl'nik, V.M. Torchinsky, V.E. Fortov, A.G. Khrapak, and K. Yoshino, *JETP Lett.*, **71**, 102 (2000)
2. B.M. Annaratone, A.G. Khrapak, A.V. Ivlev, G. Söllner, P. Bryant, R. Sütterlin, U. Konopka, K. Yoshino, M. Zuzic, H.M. Thomas, and G.E. Morfill, *Phys. Rev. E*, **63**, 036406 (2001)