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Compression Plasma Flows Action on Monocrystalline Silicon Surface

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Introduction. The action of compression plasma flows generated by quasi-stationary plasma accelerators, on various materials opens up wide prospects for modification of their surface properties. Application of such a technique to semiconductors seems to be of most interest since their surface when exposed to plasma reveals unusual sub-micron regular structures [1]. The distinctive of compression flows is the "freezing" of magnetic field into plasma. In our experiments such flows were obtained in a magnetoplasma compressor (MPC) representing one of the versions of quasi-stationary plasma accelerator [2]. Plasma flow in the MPC is compressed due to interaction between longitudinal component of current swept away from accelerating channel, and intrinsic azimuth magnetic field. The presence of a “swept-away” current in the plasma flow is caused by the magnetic field freezing in plasma.

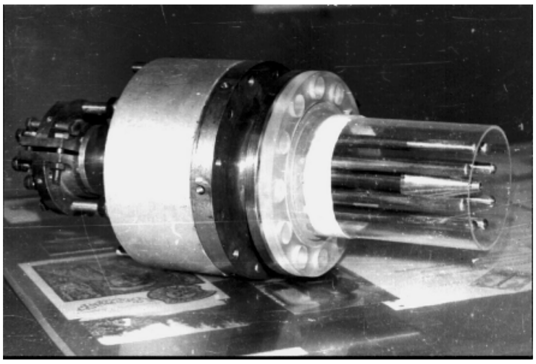
Advantages of MPC as compared to other types of accelerators are high stability of a compression flow generated, controllability of its composition, size, and plasma parameters, as well as a discharge duration sufficient for practical applications.

The paper presents results of investigations into capabilities of compression plasma flows to form highly oriented sub-micron tube-like structures on monocrystalline silicon.

Experimental setup. In experiments discussed, the compression plasma flows were obtained using a gas-discharge MPC of compact geometry powered with a capacitive storage (C_0 = 1200 μF) operating at initial voltages, U_0, from 3 up to 5 kV [3-4]. The photo of MPC discharge device is shown in Fig. 1a.

The MPC operated in the residual-gas regime wherein the pre-evacuated accelerator chamber was filled with nitrogen to a preset pressure (100–1300 Pa). The discharge duration in the MPC amounts to 120 μs and the peak value of discharge current, depending on initial parameters of discharge, ranges from 70 to 100 kA.

Under these conditions, a compression plasma flow 6–10 cm in length with diameter of 0.7-1 cm in the maximum compression zone was formed at the output of the MPC discharge device (Fig. 1b). The compression flow is stable for about 80 μs, after which it starts to diverge in



a

b

Fig. 1 a – photo of MPC discharge device;
b – sequence of photos of plasma flow; frame frequency – 250000 frame/sec

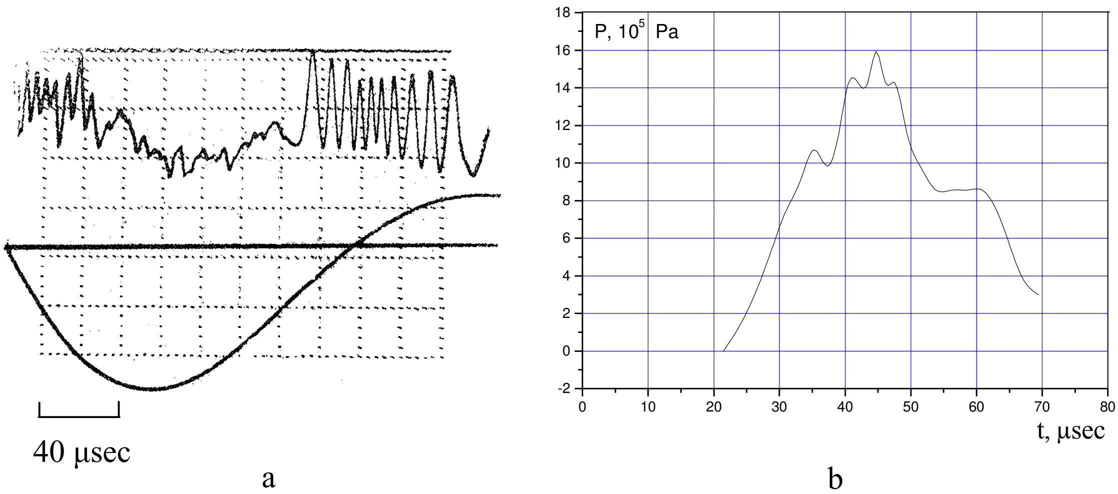
a half-angle of 5 to 15^O. The plasma velocity in a compression flow is in the range of $(4\text{-}7)\cdot10^6$ cm/s, depending on the initial parameters of the MPC. The concentration of charged particles in the maximum compression zone is as high as $(5\text{–}10)\cdot10^{17}$ cm^{-3}, and the temperature is 1–3 eV [3, 4].

The monocrystalline silicon samples (10 mm x·10·mm x 0.28 mm) of (111) and (100) crystallographic orientations were mounted at an axis of the system normally to a compression flow at distances from the tip of MPC discharge device ranging between 6 and 16 cm. The surface microrelief and the slices of single-crystal silicon samples were photographed using high-resolution scanning electron microscopy on a Hitachi S806 microscope.

Results and discussion.

Incidence of compression plasma flow on silicon surface results in the formation of shock-compressed plasma layer. According to conducted calorimetric measurements, values of energy absorbed by silicon surface depending on sample location range from 5 to 25 J per pulse, which corresponds (in our experimental conditions) to an increase in power density of a plasma flow from $0.5\cdot10^5$ to $3\cdot10^5$ W/cm^2. In its turn, density of charged particles in plasma varies from 10^{18} cm^{-3} in the region of maximum contraction to 10^{16} cm^{-3} in the area of compression flow divergence.

Temporal dependence of impact pressure developed by incident plasma flow on the surface of samples mounted at various distances (8 to 20 cm) from the accelerator outlet was recorded by the use of an optical pressure sensor. Such a sensor is not adversely affected by electric or magnetic fields and does not have to be calibrated. The MPC initial voltage ranged from 3 to 5 kV. The pressure sensor featuring a rather extended optical element made it possible the undistorted signals of ~ 100 μs duration to be recorded. A representative oscillogram from the sensor is shown in Fig. 2a. Relative accuracy of pressure measurements is around 10%. Depending on the target/accelerator distance and initial voltage, pressure on silicon surface ranged from 10 to 30 bar (Fig. 2b).



a b

Fig. 2. Oscillogram (a) and temporal evolution of pressure (b) for distance 12 cm

As follows from the analysis of experimental data, the action of the compression plasma flow on the sample results in the melting and subsequent modification of silicon material down to the depth of 6 μm. Cylindrical fragments 50-100 μm in length and 0.3-1 μm in diameter are formed on silicon surface (Fig. 3). Channels oriented normally to the sample surface were

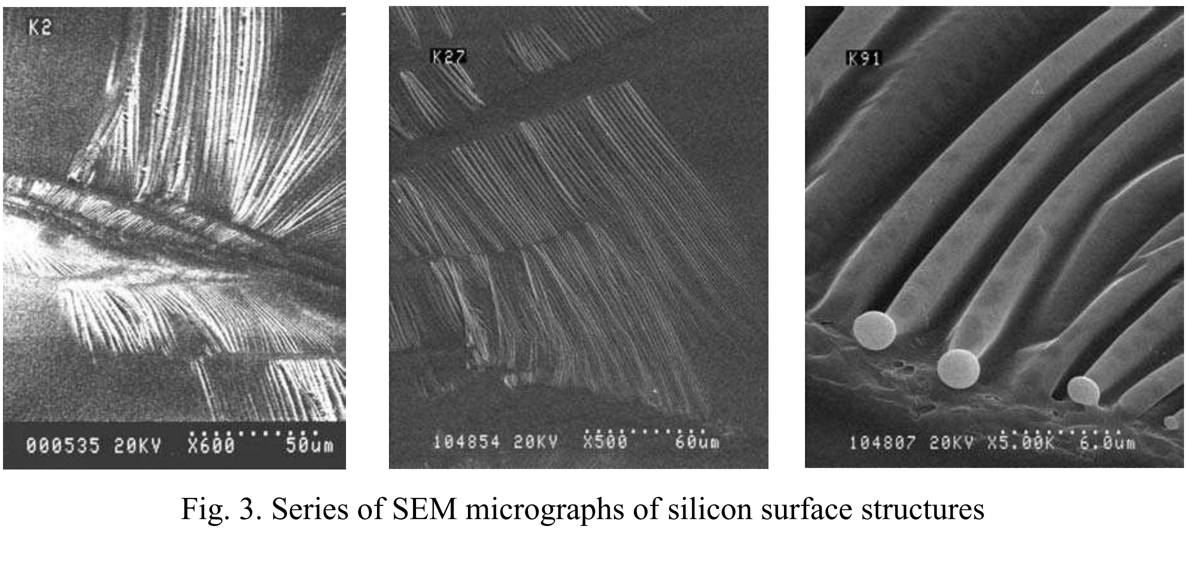


Fig. 3. Series of SEM micrographs of silicon surface structures

found to form within a modified layer (Fig. 4). The channels are about 6-12 μm long and 0.1-0.2 μm in diameter; the spacing of such structures (1-2 μm) corresponds to that of surface regular patterns formed by cylindrical fragments.

In order to clarify whether such cylindrical structures have tubular form, silicon surface was exposed to compression plasma flow with excess energy. Under hard conditions cylindrical structures are destroyed showing their interior arrangement (Fig. 5). As clearly demonstrates this SEM micrograph, the cylindrical structures are hollow.

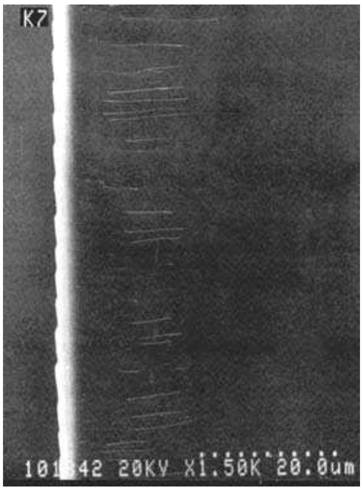


Fig. 4.

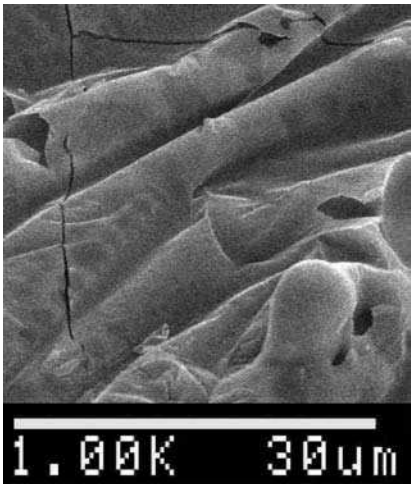


Fig. 5.

The formation of new phase on silicon surface may be caused by following main factors: high-energy action of plasma flow on silicon surface resulting in the fast heating of surface layer; the melting of surface layer; the spreading of plasma and, as a consequence, of liquid melt throughout the surface (from the sample central area outward), in response to both dynamic pressure of compression flow and gradients of thermodynamic parameters in shock-compressed layer. Distinctive feature of crystallization processes is the presence of strong magnetic fields induced by swept-away currents.

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