On the Control of the Nematic Orientation on the Silicon Surface Processed by a Focused Gallium Ion Beam

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Abstract—Preliminary results of studying the orientation of a 5CB nematic on the single-crystalline silicon surface processed by a 30-keV focused Ga ion beam are reported. It is shown that the nematic can be controllably imparted on a homeotropic or inclined orientation depending on the surface irradiation dose. By varying the scanning raster of the ion beam, one can obtain different surface patterns with a micrometer resolution and a desired orientation of the nematic.

Owing to its processing behavior and physical properties, silicon is often used as a multifunctional "platform" for developing and fabricating liquid-crystal devices, such as microdisplays, space–time modulators of light, and diffraction devices. Therefore, development of techniques making it possible to controllably obtain micrometer- and submicrometer-resolved orientations of liquid-crystal molecules on the silicon surface seems to be a burning problem.

The orientation methods based on ion [1] and plasma [2] processing of the surface and on oblique deposition of SiO_2 [3], which use low-energy (1 keV or below) beams of ions and neutrals, are of little avail for this purpose because of the need for transparent masks with the above resolution, the fabrication of which by itself is a challenge. Photo-orientation methods [4] suffer from disadvantages, such as the need for high-temperature processing of substrates and a poor photosensitivity of polymeric coatings especially when microdevices are applied in projection systems, where the surface is exposed to an intense light flux. Other orientation methods, specifically, scribing of the surface with the tip of an atomic force microscope [5] and local oxidation [6] basically can solve the problem of micrometer resolution but yield, according to published data, poorly reproducible results. Moreover, scribing is a variety of contact methods [5], which have well-known drawbacks.

Recently, focused gallium ion beams have become a popular tool in microelectronics [7], specifically, for surface processing and visualization with a nanometer-scale resolution. Since the application of focused ion beams is an undeniably promising approach, we considered in this work the feasibility of controlling the liquid crystal orientation on the silicon surface with a focused Ga ion beam.

In experiments, single-crystalline p-type silicon with a resistivity of 4.5 Ω cm was used. Its surface was processed by a 30-keV focused Ga ion beam with a current of 3 nA in an FEI Quanta 200 3D dual-beam electron/ion scanning microscope. Rectangular n^+-wells were used as reference marks on the silicon surface.

By scanning the ion beam over the silicon surface, we formed six overlapping rectangular (350 × 300 μm) areas irradiated with a different dose. Then, the silicon sample was used as a substrate to prepare a sandwich-type liquid-crystal cell. The surface opposite to the silicon substrate was processed in a lecithin solution to produce the homeotropic (normal) orientation of the liquid crystal. A 5CB nematic liquid crystal in the isotropic phase was inserted into a 5-μm-thick cell. Figure 1 demonstrates a fragment of the liquid-crystal cell with the irradiated areas mentioned above.

Fig. 1. Fragment of the liquid-crystal cell with the silicon substrate irradiated by a focused ion beam under scanning conditions. The irradiation dose is (*1*) 3.1×10^{14}, (*2*) 9.3×10^{14}, (*3*) 1.86×10^{15}, (*4*) 3.72×10^{15}, (*5*) 7.44×10^{15}, and (*6*) 1.48×10^{16} ions/cm^2.

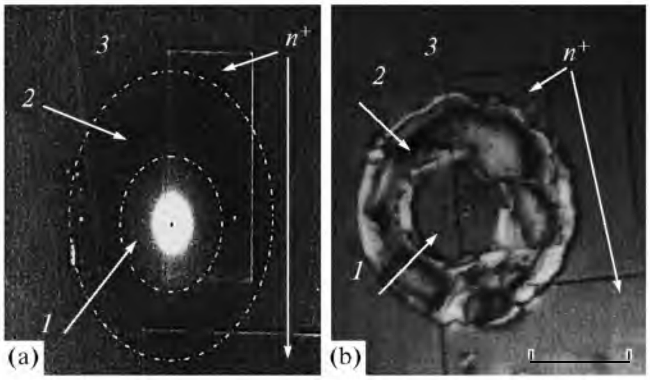

Fig. 2. (a) SEM image (taken at an angle) of the silicon surface irradiated by the ion beam spot (the exposure time is 300 s) and (b) the image of the nematic layer on the irradiated silicon surface (the scale mark equals 120 μm).

The analysis of the nematic orientation under a polarization microscope showed that the orientation of the irradiated areas considerably depends on the irradiation dose. If the surface opposite to the silicon substrate has a homeotropic orientation, the irradiation dose in the initial (first) area is insufficient to change the initial homeotropic orientation of the nematic on the silicon surface. With an increase in the irradiation dose (areas *2*–*5*), the amount of disclinations (dark curved lines) decreases. Since disclinations are regions where the long axes of nematic molecules change a preferred direction, it can be argued that the molecule orientation in the liquid crystal layer becomes more ordered with an increasing irradiation dose. The fifth area (except for boundary regions) is characterized by the almost uniform inclined orientation of the nematic, especially in the regions where this area overlaps with the fourth one. The appearance of the sixth area suggests that here the orientation of the nematic is homeotropic. Thus, from the first to the six area, the orientation of the nematic on the silicon surface varies from initial homeotropic to final also homeotropic, passing through intermediate stages of inclined orientation with a various degree of nonuniformity.

To gain a deeper insight into the resulting orientation of the nematic, the silicon surface was irradiated by ion spots; that is, the ion beam was focused into a spot on the silicon surface. In this case, the radial distribution of the ions over the beam's cross section is always characterized by a Gaussian tail [8]. Since this distribution is continuous, even a single "spotty" irradiation of the surface covers a wide range of irradiation doses.

Figure 2a shows a typical scanning electron microscope (SEM) image of the silicon surface irradiated by ion beam spots (normal incidence). Two typical regions can be distinguished on all the images of the irradiated surface: bright region *1*, which is near the crater (dark point at the center of region *1*), and region *2*, which is darker than the background of surface area *3* irradiated by an insufficient dose. Note that bright region *1* is colored nonuniformly: the brightness increases considerably toward the center. Two dashed lines in Fig. 2a separate, respectively, region *1* from region *2* and region *2* from surface area *3*, which is unprocessed (or processed by a low dose).

It is known from published data that fast Ga ions penetrating into the surface layer of silicon cause its amorphization. The surface becomes amorphous starting from a dose on the order of 10^{14} cm^{-2} (30 keV) [9]. Therefore, we may assume that bright region *1* on the ion-beam-irradiated silicon surface (see the SEM image in Fig. 2a) is amorphous.

Figure 2b is a polarization image of the nematic layer applied on the silicon surface before irradiation. It is distinctly seen that the ion beam interacting with the silicon surface forms two regions where the nematic has a homeotropic (arrow *1*) and inclined (arrow *2*) orientation. Note that the inclined orientation of the nematic in region *2* is nonuniform. The boundary between these two regions is rather sharp (Fig. 2b) and corresponds exactly to the boundary between regions *1* and *2* in the SEM images (Fig 2a, dashed line). In other words, the bright silicon surface on the SEM images imparts the nematic homeotropic orientation, while the dark surface gives rise to an inclined orientation. Note a high reproducibility of both orientations of the nematic after the liquid-crystal material has been repeatedly removed from and applied on the silicon surface (the surface was cleaned out of the liquid crystal in commercial solvents, namely, isopropyl alcohol, acetone, and dimethylformamide).

Figure 3 shows the images of the nematic layer on the silicon surface under the conditions of oblique spotty irradiation. It is distinctly seen that regions in which the orientation of the nematic has changed to both homeotropic (region *1*) and inclined (region *2*) and which contain a number of disclinations (one of them is indicated in Fig. 3a) represent elliptical zones. The ellipticity of the orientation zones rules out the possibility that the orientation of the nematic changes on a deposited layer that could basically form from substrate material particles ejected from the crater (like from a point source) under the action of the focused ion beam. If it were so, the zones of changed orientation would have a ring structure, which is not the case in the experiment. The examination of the silicon surface under an Integra NT-MDT atomic force microscope (AFM) showed that the focused ion beam changes the silicon surface relief via the rupture and sputtering of the substrate material only in the neighborhood (within 10 μm) of the crater. The rest of the surface remains intact, as follows from the AFM images.

It can be shown qualitatively that the pretilt angle of nematic molecules in the region with inclined orientation varies with distance to the center and takes a minimal value at some irradiation dose. Mechanically shifting the liquid-crystal material toward the regions with changed orientation, one can decrease the thickness of the nematic so that the remaining layer appears bright in polarized light (region *2*) but without interference false coloration, the dark background of region *1* with homeotropic orientation remaining unchanged irrespective of the nematic thickness (see Fig. 3a). The absence of interference means that the thickness of the liquid-crystal (birefringent) layer is such that the optical path difference is insufficient for the ordinary and extraordinary rays to interfere. In the case of the liquid crystal backflow, the thickness of the layer gradually grows and finally the interference condition is fulfilled. The dash-and-dot line in Fig. 3a outlines the region where the false coloration of the nematic appears for the first time. This indicates that the optical path difference between the ordinary and extraordinary rays along the circumference of the outlined ellipse reaches a maximum at this time instant. This, in turn, means that the pretilt angle in the given area of the liquid crystal (marked by an arrow in Fig. 3a) is minimal. As the thickness of the layer grows, so does the optical path difference, so that the interference condition is sequentially met in other elliptical zones far from the first ellipse (Fig. 3b). Note that the number of disclinations in inclined orientation region *2* (Fig. 3a) diminishes from the periphery to the center with an increasing dose, as in the case of raster irradiation of the silicon surface (Fig. 1).

It should be noted that the sharp boundaries of the regions with the homeotropic and inclined orientation of the nematic (Figs. 2b, 3) on the silicon surface irradiated by ion spots suggest that the variation of the nematic orientation with the irradiation dose may have a threshold.

The main factor that seems to be responsible for the homeotropic orientation of the nematic is the amorphization of the silicon surface upon ion-beam irradiation with an appropriate dose. The abovementioned good correlation between the appearance of the homeotropic texture of the nematic and the appearance of bright coloration on the same area of the silicon surface in the SEM image (Fig. 2) is a qualitative substantiation of this assumption. The inclined orientation of the nematic may be due to the hydrophilic/hydrophobic properties of the silicon surface (this factor “works” at a lower dose). Owing to hydroxyl groups present on the surface [10], silicon tends to align the 5CB polar nematic homeotropically. During irradiation, the surface adsorbs Ga ions and they partially substitute hydroxyl groups [11]. Under such conditions, the hydrophilic properties are partially lost and, hence, the tendency to homeotropically align the nematic partially abates.

Thus, it was demonstrated experimentally that one can impart a homeotropic or inclined orientation to the 5CB nematic on the silicon surface by exposing the surface to a Ga ion beam with an appropriate irradiation dose and varying the pretilt angle in the region of inclined orientation within some limits where it passes through a minimal value. The surface pattern with a micrometer resolution and a desired orientation of the nematic is governed by the ion beam raster.

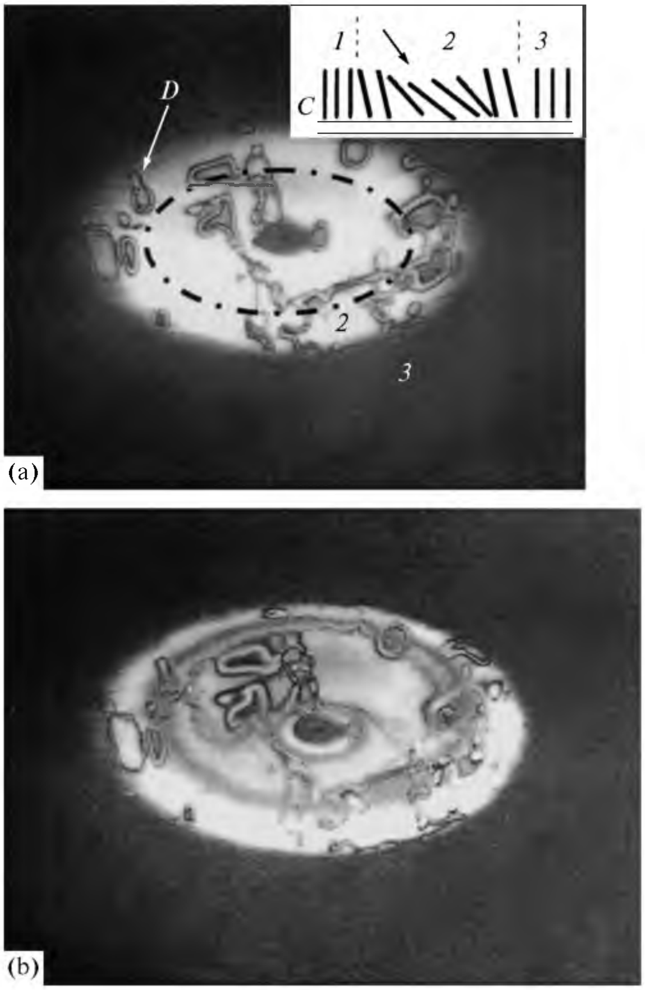

Fig. 3. Orientation of the nematic on the silicon surface in the region of inclined spotty irradiation by the ion beam (*D* is a disclination). The exposure time is 100 s. The false coloration of the elliptic zones is (a) absent and (b) present. The inset schematically shows the (*1*) homeotropic, (*2*) inclined, and (*3*) initial homeotropic orientation of nematic molecules on the silicon surface (*C* is the zone of the crater).

ACKNOWLEDGMENTS

The authors thank the Shared Service Center at the Belgorod State University for the assignation of necessary equipment.

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