REORIENTATION OF A NEMATIC IN THE VICINITY OF MECHANICAL DEFECTS OF THE SILICON SURFACE

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We study the reorientation of a nematic liquid crystal in the vicinity of defects of the silicon surface (cracks, scratches) in structures of the Al/Si/nematic/ITO type. It is shown that, in the vicinity of a typical mechanical defect of the silicon surface with linear sizes of the order of tenths of a micron, a localized region of the homogeneously reoriented nematic is formed, whose size depends on the frequency, voltage, and size of the very defect. It is shown that the formation of a domain is defined by the process of nonstationary depletion of the silicon surface, the creation of a high-resistance near-surface layer, and the enhanced currents flowing through the liquid crystal — silicon interface, which hampers the formation of a depleted layer in the vicinity of defects. We demonstrate a method allowing the visualization of a crack on the silicon surface. The method is based on both the simultaneous formation of a Si surface layer depleted by major charge carriers and the generation of nonequilibrium charge carriers, which is inhomogeneous over the surface area, by a laser emission. It is established that the method allows one to detect cracks of several tens of nanometers in depth on the silicon surface.

Introduction

The quality of the silicon surfaces must satisfy the tough requirements, because all the active elements of microcircuits are formed in the near-surface region of silicon [1]. One of the widespread types of surface defects, which are controlled in the production of silicon microcircuits, are microcracks and microscratches. The control is carried out mainly by optical methods and scanning electron microscopy (SEM). Optical methods become inefficient if the sizes of cracks are of the order of a light wavelength, and the preliminary charting of the surface should be performed for SEM to be efficient.

As a promising method of detection of microcracks and microscratches on silicon surfaces, we mention the method of liquid crystals (LC) [2]. Due to certain specific properties, the LC medium can play the role of an optical amplifier of inhomogeneities of the surface of silicon, by allowing their visualization. In this case, the tested surface area does not restricted. Moreover, if the surface defects are a source of inhomogeneous electric fields, then a LC will visualize also the inhomogeneities of electric fields due to its electrooptical properties [3].

The production of Si devices uses widely silicon with the specific resistance of the order of several Ω×cm which is less by many orders than the specific resistance of LC materials. Therefore, in the classical type of LC cells possessing the typical Si/nematic/ITO structure, the main part of the voltage applied to a cell will drop on the LC layer, if no special measures are used. For this reason, inhomogeneities of the silicon surface cannot induce a considerable change in the voltage drop on a LC. Therefore, inhomogeneities cannot be visualize by LC. To visualize the surface inhomogeneities which include microcracks and microscratches, the mode of nonstationary excitation of a Si specimen should be employed. In this case, certain phases of the alternating voltage are characterized by the appearance of a high-resistance state, in which the resistances of the Si surface layer and the LC layer take comparable values [4, 5]. The purpose of the present work is the demonstration of the visualization of mechanical defects (microcracks and microscratches) of the surface of silicon in the nonstationary mode of excitation of the Si/nematic/ITO structure. We consider the physical processes running in a LC in the vicinity of defects of silicon and in the very Si.

1. Experiment

We tested the surface of a monocrystalline silicon of the n-type of conduction, whose specific resistance is of the order of 4.5 Ω×cm. To form a plane orientation of a nematic liquid crystal 5CB, a transparent electrode in the Si/5CB/ITO structure was covered by a film of rubbed polyimide. The surface of silicon is not cover by orienting films in the general case. The LC thickness was controlled by the interference method and was of the order of 1 μm.

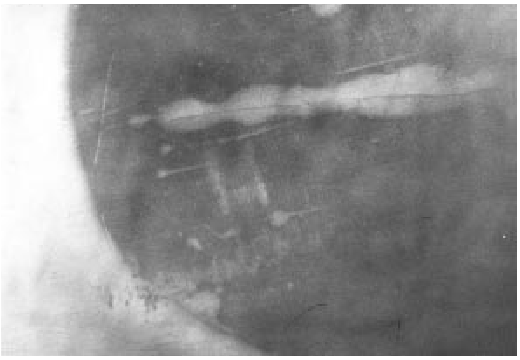


Fig. 1. Reoriented region of a nematic (a domain) in the vicinity of a microcrack on the Si surface in the Si/5CB/ structure. The frequency of the testing voltage is 10^5 Hz; its amplitude is 3.9 V

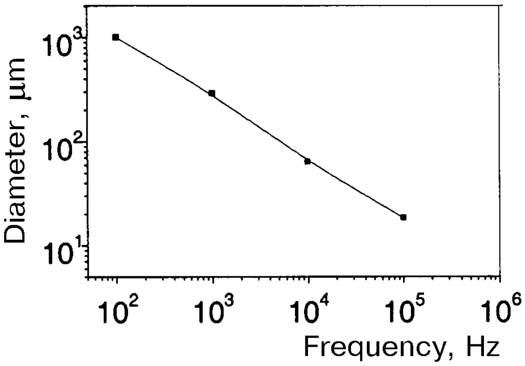


Fig. 2. Diameter of a typical domain vs the frequency of the applied voltage $U = 4.1$ V in the Al/Si/5CB/ITO structure

After the application of an alternating voltage to a cell, the regions of the reoriented nematic were formed in the vicinity of mechanical defects of the silicon surface (Fig. 1). These regions have a good contrast in a polarized light, and their sizes are, in the general case, by one order more than those of the surface defects inducing these regions.

Fig. 2 shows the typical dependence of a stationary size of a domain on the alternating voltage frequency. As seen, this dependence is quite strong.

With the purpose to study the properties of domains and the mechanism of their formation, we carried out the additional experiments, in which the cell contained a specimen made of silicon of the *n*-type conduction ($\sim$ 4.5 Ω·cm). In its surface layer, the cavities highly doped with a donor ($n^+ \sim 10^{19}$ cm^{-3}) with depth $H \sim 30$ nm were formed [6]. Such a structure of silicon in an LC cell allows one to qualitatively test the width of a depleted layer L by using the electrooptical reaction of LC and to estimate the value and sign of a surface charge [6].

All manufactured and tested cells can be qualitatively divided into 3 types by the ratio of the width of a depleted layer L and the depth of cavities in silicon H.

For the first type of cells, $L \sim 0$. In this case, a depleted layer is absent, and all voltage U applied to a cell drops on the LC layer. Obviously, cavities are not visualized in such cells.

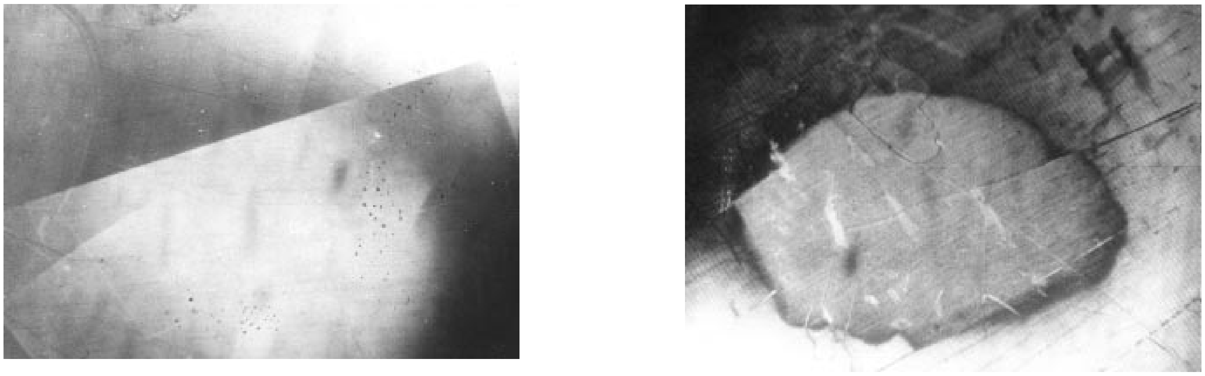
For the second type of cells, $0 < L < H$. In this case, cavities are visualized by LC, because the voltage drop on cavities is infinitely small, whereas a part of the external voltage on the sections between cavities drops on the high-resistance surface layer of silicon. That is, we observe a potential relief in the plane of a cell.

For the third type of cells, $L > H$. In this case, cavities are not visualized by LC, because Si is depleted everywhere (under cavities as well).

These 3 types of cells well differ between themselves by the reaction of a cell on the emission of a He—Ne laser ($\sim$ 2 mW, 0.63 μm).

Cells of the first type are insensitive to light. For cells of the second type, the electrooptical reaction is the reorientation of LC in the region of a laser spot, and cells of the third type react on the emission of a He—Ne laser in such a way that LC is uniformly reoriented above segments of the Si surface. Segments are separated one from another by cracks (Fig. 3,*a*). Of a certain interest is the reaction which is a mixture of two last variants. In this case, the reoriented region of the nematic in a laser spot is framed by straight lines, being cracks on the Si surface (Fig. 3,*b*).

The reason for the effect of “segmentation” of the Si surface in a nematic cell under the illumination with a laser is as follows. If a voltage is applied on a cell, and the Si surface is not illuminated by a laser emission, the depth of a depleted layer L (Fig. 4) is the same over a cell. When the cell is illuminated by a laser emission with a nonuniform distribution of the light intensity over the surface, the depletion boundary is lifted due to the generation of inequilibrium charge carriers in Si. Segments of the depleted surface layer in silicon are separated, cracks become isolated one from another, and the levels L^* in all the segments of the surface are generally different (Fig. 4). Due to the fact that the resistances of different segments are different, the electrooptical reaction of the LC layers above these segments will be also different. This allows one to localize a crack between adjacent segments of the silicon surface in the polarized light (see Fig. 3,*a*). The analysis of



a **b**

Fig. 3. Electrooptical reaction of LC in the Al/Si/5CB/ITO structure on the laser emission of a He—Ne laser. Frequency — 10^5 Hz, voltage — 3.9 V: *a* — effect of "segmentation" over cracks of the Si surface. *b* — partial "segmentation" along the perimeter of a laser spot

images of the cracked surface of silicon, which were obtained with the help of an atomic force microscope (AFM, Digital Instruments NanoScope IIIa, tapping mode), showed the following. By varying such parameters as the incidence angle of a laser beam on the Si surface, frequency and amplitude of a voltage, and position of a laser spot on the Si surface relative to the very crack, we can visualize cracks of the order of several tens of nanometers in depth on the Si surface.

Because the Si surface has a direct contact with LC, ions with different signs can be adsorbed on it during the application of LC, i.e., in the process of preparation of a cell. Therefore, the Si surface can be depleted or enriched by charge carriers depending on the sign of adsorbed ions. Since the process of adsorption remains uncontrolled, the cells appeared after the preparation correspond, as a rule, to all three above-mentioned types approximately in the same proportion. It is established that the covering of the silicon surface with a polyimide film, which is used for the formation of a more qualitative plane orientation of a nematic, increases generally the probability for the cell to belong to the second type.

It was established in the course of experiments that domains are induced by defects of the silicon surface in the case where cells belong to the second type. Such a regularity can be explained as follows. At the initial time moment after the switching on of an alternating voltage, the lower part of the majority of cracks is positioned in the nondepleted Si. Therefore, currents flow both from LC to Si (j_1) and from Si to LC (j_2). Those flowing through the developed surface of cracks (1 in Fig. 5) are more than analogous currents flowing through the defectless surface of silicon (Fig. 5). The current j_1 hampers the formation of a depleted layer in the surface layer of silicon at a distance $\sim D/2$ from the crack (Fig. 5), i.e., the current j_1 defines the domain size. As a result of the passage of the current j_2, a negative ion charge Q is accumulated in LC. We consider that the carriers in LC which exchange a charge with Si can be only negatively charged ions appearing on the cathode due to the electrochemical reaction of attachment of an electron to a neutral molecule.

The above-proposed mechanism agrees with the following experimental fact. The domain size increases with the voltage of a certain frequency. If we begin to decrease the voltage after the attainment of some value U^*, we observe the disappearance of domains by approaching the previous value of the voltage, and the reaction of the cell on a laser emission will correspond, to a greater extent, to the variant of the visualization of segments (Fig. 3,*a*). This means that, during the time when the enhanced voltage U^* acts on a cell, a nonequilibrium ion charge exceeding the equilibrium value is accumulated in LC as a result of the passage of the enhanced current j_2 across every segment of the surface of silicon. This occurs more intensively in the vicinity of a microcrack. When the voltage decreases to the previous value, j_1 also decreases, but the superfluous ion charge cannot relax so rapidly. Therefore, this charge additionally depletes the Si surface due to the field effect. Due to the depletion, the boundary L descends below the lower boundary of the majority of typical cracks, which is accompanied by the disappearance of domains.

The return of a cell into the state corresponding to the visualization of domains occurs for a quite long time. For example, let us consider cells, whose Si surface is

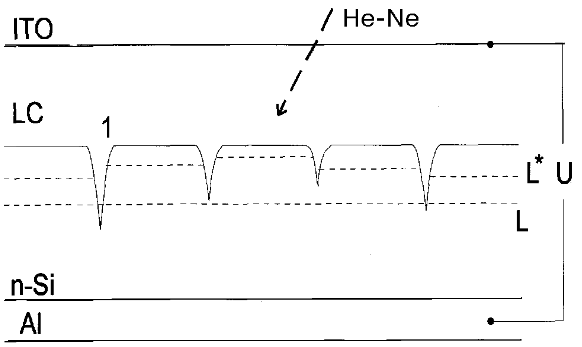


Fig. 4. Scheme of a change in the depletion of Si in the structure under He—Ne laser illumination

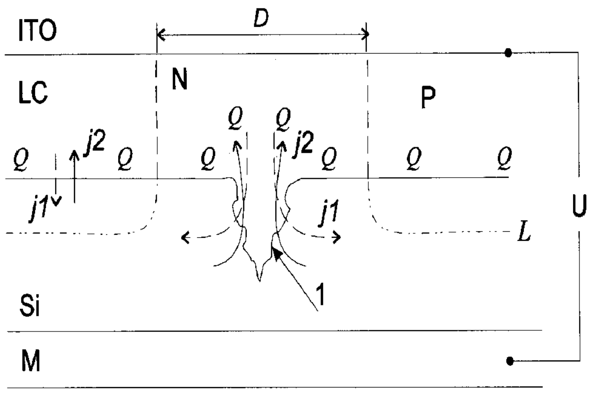


Fig. 5. *LC* — liquid crystal, *P* and *N* — plane and homeotropic orientation of a nematic, *D* — domain size, *Q* — accumulated charge, *L* — boundary of a depleted layer, *U* — voltage supplied on a cell, *1* — crack

covered with a polyimide film. For them, the return duration is about $2{\cdot}10^3$ s for the maximum U^* equal to 10 V at a frequency of 10^5 Hz.

Thus, we have shown that mechanical defects of the silicon surface in a nematic cell can induce the localized regions of a reoriented nematic (domains). The condition for the appearance of domains is a depletion of the Si surface, and the depletion boundary should not excess the depth of cracks on the Si surface. We have developed a simple LC-based method which allows one to detect microcracks on the surface of silicon. The method is based on the nonuniform generation of nonequilibrium carriers in the depleted layer of silicon. A crack is visualized due to the different electrooptical reactions of a nematic above adjacent segments of the surface of silicon which are separated by the crack.

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ПЕРЕОРІЄНТАЦІЯ НЕМАТИКА В ОКОЛІ МЕХАНІЧНИХ ДЕФЕКТІВ ПОВЕРХНІ КРЕМНІЮ

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Резюме

Досліджено переорієнтацію нематичного рідкого кристала (РК) в околі дефектів поверхні кремнію (тріщин, подряпин) в структурах типу Al/Si/нематик/ITO. Показано, що в околі типового механічного дефекту поверхні кремнію з лінійними розмірами порядку часток мікрона формується локалізована область однорідно переорієнтованого нематика, розміри якої залежать від частоти та амплітуди напруги, а також від розміру самого дефекту. Показано, що формування домену пов'язане з процесом нестаціонарного збіднення поверхні кремнію та з формуванням високоомного приповерхневого шару, а також завищеними струмами витоку крізь межу РК—кремній, що перешкоджує формуванню в околі дефектів збідненого шару. Описано метод, який дозволяє візуалізувати тріщини на поверхні кремнію. Метод базується на індукуванні в кремнії поверхневого шару, збідненого основними носіями заряду, та на неоднорідній по площі одночасній генерації нерівноважних носіїв заряду лазерним випромінюванням. Встановлено, що метод дозволяє розрізняти на поверхні кремнію тріщини глибиною порядку декількох десятків нанометрів.