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ASSESSMENT OF CHANGES IN THE TEXTURE OF THE SILICON SURFACE UNDER THE INFLUENCE OF A MAGNETIC FIELD AND HIGH-TEMPERATURE PLASTIC DEFORMATION USING FRACTAL ANALYSIS

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Materials based on silicon are widely used in energy, electronic devices, solar cells, optoelectronics, and the electronics industry. A current challenge is the controlled use of these materials in technologies under mechanical loads, radiation, and magnetic fields. The aim of the study is to investigate the change in the surface texture of silicon under the influence of a magnetic field and high-temperature plastic deformation using fractal analysis.

The material for the study consisted of n-Si monocrystalline silicon wafers grown by the Czochralski method (Si-CZ), with controlled damage applied to the surface using a diamond indenter. The study employed a method to investigate dislocation movement in silicon single crystals under high-temperature plastic deformation. The experimental technique combines several materials science methods: deformation by the four-point bending test, annealing, chemical etching, and microscopy. In addition to high-temperature plastic deformation, silicon was treated in a magnetic field. The sample was placed between the poles of an electromagnet to create a magnetic field. The magnetic induction vector was perpendicular to the induced scratch.

The analysis and description technique combines visual observation of photographs and fractal analysis of microimages of the chemically etched surface of silicon. Within the framework of fractal analysis, fractal dimension and lacunarity indicators were determined, which describe the unevenness and complexity of the dislocation structure of the surface. The obtained images revealed numerous dislocation exits on the surface located around the artificially created scratch, as well as changes in the surface texture.

Magnetic treatment leads to the segregation of silicon atoms and impurities at the surface and the formation of a granular structure on the wafer surface. In this case, the fractality of the surface of the samples increases, while lacunarity decreases. It has been shown that under the influence of a weak magnetic field, the stabilization or blocking of the movement of already existing dislocations is possible. After turning off the field, the energy in the system is insufficient for these defects to activate and begin to move even after a second round of annealing and load. This behaviour allows for the use of sample treatment in a magnetic field to obtain defect-free silicon structures.

***Keywords**: single-crystal silicon, energy, microelectronics technology, surface texture for biochips, magnetic field, high-temperature deformation, etching pits, dislocations, fractal analysis, impurities, microimages*

INTRODUCTION

Materials based on silicon are widely used, especially the wafers grown using the Czochralski method (Si-CZ), in solar cells and the electronics industry [1, 2]. On one hand, the semiconductor and diamagnetic properties of such materials can be significantly and controllably altered by impurities and dopants, which opens new possibilities for further applications. On the other hand, defects in crystalline silicon can negatively affect the performance of the products. An important issue is the development of new silicon-based materials and methods for technological purification from defects in these materials, which are needed for energy and other industries where silicon use involves mechanical loads, radiation, and weak magnetic fields.

Weak magnetic fields are those in which the condition is met: $\mu B < k_B T$, where μ is the Bohr magneton, B is the magnetic field induction, k_B is the Boltzmann constant, and T is the temperature. For example, for room temperature

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($T = 295$ K), a magnetic field with induction $B << 400$ T can be considered weak.

Experimental and simulation results on the influence of a magnetic field on doped silicon crystals indicate intrinsic magnetism at the silicon surfaces [3], changes in the Fermi-level position at the surface compared to the values for bulk doping concentrations [4], alterations in conductivity and the electrophysical properties of surface structures [5], plasticization effects [6], reduction in photoconductivity after exposure to a magnetic field [7], and transformations in the microdefect structure of silicon crystals [8]. Isothermal annealing reveals the possibility of reducing the density of structural defects in silicon wafers [9], as well as an increase in the paramagnetic component of magnetic susceptibility and microhardness, linked to the restructuring of the single-crystal silicon structure [10]. Despite the available experimental information on this topic, there is still no complete theory or experimental studies regarding changes in surface topology and the dependence of dislocation movement in semiconductors subjected to high-temperature plastic deformation and exposure to a magnetic field (hereinafter referred to as MF). Reliable information on the distinction between the roles of different types of barriers and stoppers that either prevent or accelerate dislocation propagation is lacking.

In most cases, the explanation of material behaviour in a magnetic field is associated with thermal heating of the sample. However, in the case of weak magnetic fields for silicon, this justification is no longer sufficient, and additional methods for describing behaviour in a magnetic field are needed to significantly expand our understanding. One promising method for studying structures and solving the problem is fractal analysis of the silicon surface using images obtained through optical, electron, or atomic force microscopy of the material [11–13]. This approach enables the identification of small details in the images and determination of correlations between the fractal properties of the surface texture and the material's physical characteristics.

The aim of this work is to study the change in the texture of the silicon surface under the influence of a magnetic field and high-temperature plastic deformation using fractal analysis.

MATERIALS AND METHODS

The material used in this study was single-crystal silicon wafers with dimensions of $20.0 \times 3.4 \times 0.3$ mm^3 along the crystallographic directions [110], [112], and [111], respectively, with a surface orientation of {111}. The silicon single crystals were doped with phosphorus during growth by the Czochralski method (Si-CZ) to a resistivity of 4.5 Ohm·cm [14].

This work utilizes a method for studying the movement of dislocations in silicon single crystals under high-temperature plastic deformation. We use four-point flexural test ASTM C 1211 – 02: Standard test method for flexural strength of advanced ceramics at elevated temperatures [15]. The experimental technique combines several materials science methods: deformation using the four-point bending method, annealing, chemical etching, and microscopy. The key stages are outlined as follows:

Stage 1 – Scratch Creation: Controlled damage (scrape) is applied to the silicon surface using a diamond indenter from the PMT-3m microhardness tester, creating points of deformation localization that act as sources of dislocations.

Stage 2 – High-Temperature Plastic Deformation: The silicon sample is deformed using the four-point bending method with high-temperature annealing at 923 K, which activates dislocations and stimulates their movement under mechanical stress (Fig. 1). The movement of surface dislocation loops occurs under tensile stresses of 60–70 MPa by bending the silicon wafer for 30 min.

Stage 3 – Chemical Etching: Selective chemical etching is performed at 300 K in a Sirtle etching chamber ($Cr_2O_3 : H_2O : HF = 1 : 2 : 3$), allowing for the detection of dislocations on the silicon surface and the study of their density and mobility after high-temperature deformation.

Stage 4 – Observation: Dislocation structures on the surface of the silicon single crystal are observed and photographed using a MIM-8M metallographic microscope. The eyepiece micrometer of the microscope allows for accurate measurement of the dislocation path length after deformation and etching, with a measurement error of 1 %, ensuring high accuracy.

Stage 5 – Repeated Loading: The silicon sample is subjected to repeated loading following the same procedure as in Stage 2 to compare the behaviour of dislocations after the initial and repeated deformations. This loading is carried out at the temperature of 873 K for 90 minutes with tensile stresses of 65 MPa by bending the silicon wafer.

Stage 6 – Repeated Chemical Etching: A second round of chemical etching, as described in Stage 3, is performed to capture the new configuration of dislocations and any changes in the material's structure.

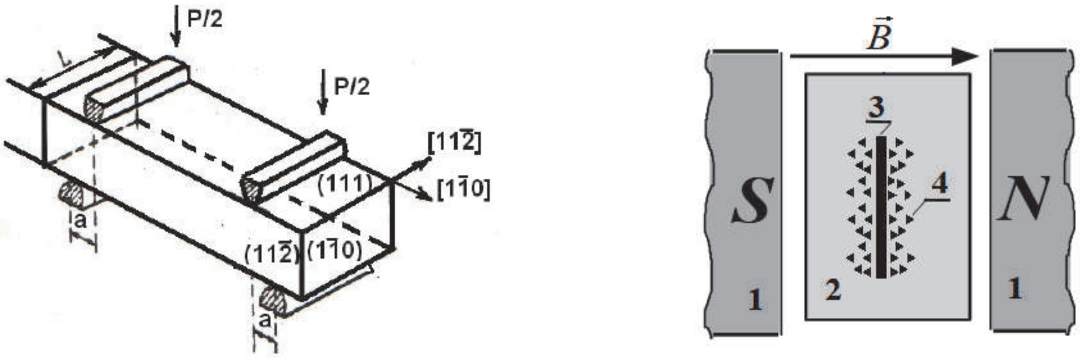
Stage 7 – Repeated Observation: In this stage, the dislocation path length is recalculated, following the same procedure as Stage 4.

The experimental procedure consisted of a cycle of Stages 1–7, followed by data analysis for two types of samples:

– Type 1 (Control Samples): These samples followed the standard procedure as described in Stages 1–7.

– Type 2 (Samples with MF Treatment): After Stage 3, additional magnetic treatment was applied in a modulated constant MF. This allows for the study of how the magnetic field affects changes in surface texture, mobility and the behaviour of dislocations in the material.

For the magnetic treatment, the test sample was placed between the poles of an electromagnet to generate a magnetic field with an induction value of $B = 0.33$ T. The magnetic treatment lasted for 180 minutes. The magnetic induction vector was perpendicular to the applied scratch (Fig. 1 *b*). The time interval between the end of the magnetic treatment and the start of high-temperature plastic deformation did not exceed 5 minutes.



a *b*

Fig. 1. *a* – diagram of the four-point bending test for a monocrystalline silicon wafer under load ($P = mg = 5.89$ N); *b* – diagram of the location of a silicon wafer (sample) with a scratch between the poles of the magnet: *1* – MF poles; *2* – silicon wafer; *3* – scratch; *4* – pits of etching of surface dislocations at Stages 4 and 7

Fractal Analysis. Fractal analysis allows for the quantitative assessment of the complexity of silicon surface structures after plastic deformation and exposure to MF. The primary metrics for image evaluation are fractal dimension (denoted as D) and lacunarity (denoted as L), which indicate the unevenness and complexity of the dislocation structure on the surface. Since quasi-fractals are formed by dislocations and other structures on the silicon surface, this method enables a description of the surface using physical fractality and quantitative estimates. Lacunarity is an indicator of the uniformity of the distribution of structures or the space between the elements of the structure. High lacunarity signifies the presence of large voids or inhomogeneities of voids within the structure. The fractal analysis was performed using the *ImageJ* program with the *FracLac* plugin, following the corresponding steps for evaluation.

1) Pre-selection of the Image Area: The parts of the image outside the field of view of the microscope or those that were unilluminated were cropped. The solid dislocation (scratch), which was introduced during the stage of controlled damage, was isolated in the image for analysis. Artifacts, such as the eyepiece ruler, were not removed, as they were needed to determine the scale, where each scale division corresponds to 10 μm.

2) Image Conversion to Binary Form: The color image was converted to a binary (black and white) form.

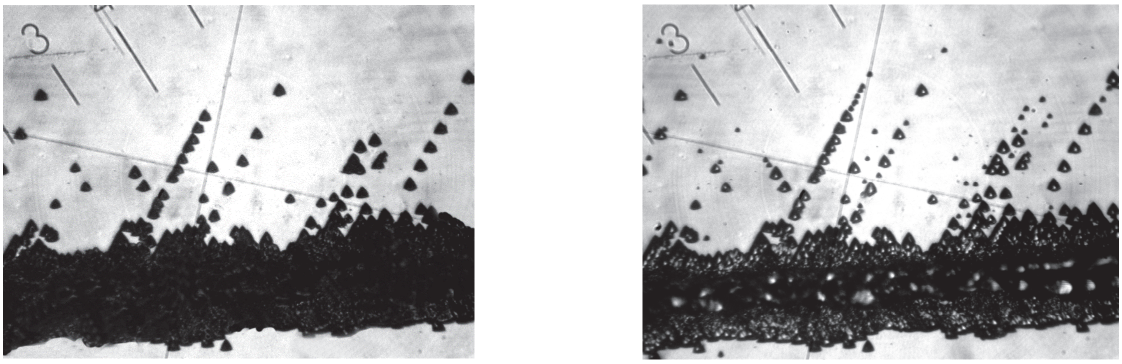
3) Calculation of Physical Fractal Dimension and Lacunarity: The primary method used for calculating the fractal dimension was *Box Counting*, with default settings. The statistical measurement error for the fractality index D was determined in the *ImageJ* program as the standard deviation. The measurement error for the lacunarity index L was calculated within the 95 % confidence interval. The multiple correlation coefficient R^2 was approximately 0.99 for both parameters.

4) Comparison of Control and Magnetically Treated Samples: A comparison of the fractal dimension and lacunarity between the control samples (Type 1) and those treated in a magnetic field (Type 2) was conducted at a fixed distance (25 μm) from the edge of the scratch. This approach allows for the assessment of the effect of magnetic treatment on dislocation movement and changes in surface texture.

RESULTS AND DISCUSSION

Changes in the surface of single-crystal silicon after the introduction of dislocations by applying a scratch were visualized through microimaging of the chemically etched surface using an optical microscope (metallography). The obtained images revealed the scratch itself, numerous dislocation exits to the surface located near the scratch, and changes in the surface texture. Let us examine the results in more detail and sequentially.

Image of the silicon surface and the movement of dislocations without MF treatment. A detailed comparison of the microimages of the chemically etched surface of a Type 1 monosilicon wafer is shown in Fig. 2. This figure compares changes in the structure near the scratch at Stage 4 (with dislocations formed after Stage 2) and at Stage 7 (after the second load and annealing).



a *b*

Fig. 2. Microimages of the structure of the etched Type 1 silicon wafer near the scratch: *a* – after the first loading, at Stage 4, *b* – after the second loading and annealing, at Stage 7. New small etching pits (triangles) are formed next to the initial large ones in an orderly pattern: a small triangle is located next to the large one

Let us apply fractal analysis to the images in Fig. 2. The fractal dimension and lacunarity for Type 1 samples at Stage 3 were $D = 1.33 \pm 0.02$ and $L = 0.91 \pm 0.03$, respectively. The corresponding data for Type 1 samples at Stage 7 were $D = 1.37 \pm 0.02$, $L = 0.92 \pm 0.03$ **(**Fig. 2 *b*). As one can observe, the results do not differ significantly after repeated loading: the fractal dimension increases slightly, while the lacunarity remains almost unchanged.

In Fig. 2 *a*, it can be seen that at Stage 2, a sequence of dislocations is formed along the crystal axis direction. Clusters of dislocations are oriented at an angle of 60º to the scratch line and at an angle of 30º to the direction of the magnetic induction vector B. The dislocation loops end in pyramidal cavities on the etched surface of the plate (etching pits, represented as black pyramids in Fig. 1–2).

After the second loading of the control samples and etching, the dislocations are set in motion (Fig. 2 *a* → Fig. 2 *b*). New small etching pits are formed next to the initial large pits in an orderly manner. At Stage 5, the dislocation detaches and begins to move, which can be observed at Stage 7 by the appearance of new small pyramids along the pre-defined lines, at a certain distance from the initially created large pyramids. Thus, without MF treatment, the mobility of dislocations remains high and can be estimated by the distance between the small and large pyramids, as well as the thermal annealing time. In the case under consideration, the average speed of dislocation movement in the control samples was 0.03 μm/s.

Another noticeable change in the control samples at Stage 7 (Fig. 2 *b*) is the appearance of white spots or speckles inside the large etching pits (within the large triangles, which represent the primary dislocations after Stage 2). These white spots are likely zones of impurity segregation, where silicon atoms and defects accumulate on the surface due to disruption of the crystal structure. Such impurities are inherently present in the initial silicon samples due to the wafer manufacturing process. In other words, the etching pit (large triangle) is partially healed by the release of atoms to the surface.

The effect of MF on the texture of the silicon surface and the mobility of dislocations. Fig. 3 shows a portion of the scratch, numerous dislocation exits to the surface (etching pits in the form of black pyramids), and an additional granular (or "curly") structure with a high density of such grains on the surface. After exposing the plate to a magnetic field with an induction of 0.33 T for 3 hours, the surface structure of the silicon plate at the final Stage 7 changes radically. However, the pattern of the primary dislocations (from Stage 3) remains unchanged. Specifically, instead of the clean background observed in Fig. 2, curls and impurity grains appear on the surface of the silicon sample (Fig. 3). Thus, as a result of the MF treatment, a magnetically induced stop of dislocations occurs on the surface of Type 2 samples, which can be observed at Stage 7 when comparing Fig. 2 and Fig. 3.

In order to calculate the fractal dimension and lacunarity, two areas, A and B, of the same size were selected from the image of the Type 2 silicon surface at Stage 7 (Fig. 3). The fractal dimension and lacunarity for these samples were as follows: for zone A – $D = 1.81 \pm 0.02$, $L = 0.34 \pm 0.03$; for zone B – $D = 1.77 \pm 0.04$; $L = 0.50 \pm 0.03$. One can see that in the absence of dislocations, the lacunarity increased more significantly than the fractal dimension. In the absence of a significant number of dislocations on one side of the scratch, it is the increased lacunarity parameter that indicates the heterogeneity of the structure (surface background). Thus, the results suggest that the fractal dimension is not significantly influenced by dislocations but is instead affected by the impurity texture of the plate surface.

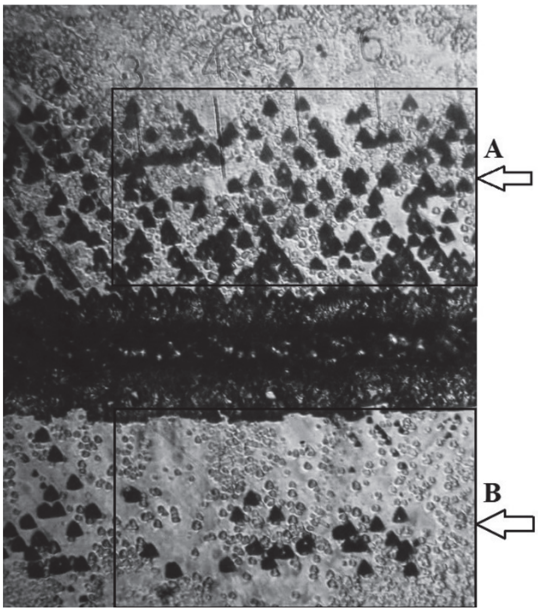


Fig. 3. Microimage of the chemically etched surface of a Type 2 silicon wafer at Stage 7, after the second loading and annealing. Zone A exhibits a high density of dislocations, while zone B is dominated by a texture of surface grains formed by impurities

In Fig. 3, it can be observed that the microimages of Type 2 samples at Stage 7 not only show the absence of small new pyramids (etching triangles) after the second high-temperature plastic deformation, but also reveal that the grainy impurities induced by the MF treatment are distributed across the entire surface of the silicon wafer, not just in the region with a high density of black pyramids. This raises the question of how to interpret these grains: Are they the result of segregation of silicon atoms or impurities from within the wafer to the surface, or is it due to surface absorption of atoms from the surrounding?

For completeness, we will evaluate the change in the texture of the silicon wafer surface in different areas of the wafer using fractal analysis (Fig. 4). The evaluation of the grain structure of the Type 2 silicon surface at Stage 7 (Fig. 4) using fractal analysis yields the following results:

– in zone C: $D = 1.75 \pm 0.04$ and $L = 0.37 \pm 0.03$
– in zone E: $D = 1.79 \pm 0.04$ and $L = 0.54 \pm 0.03$
– in zone F: $D = 1.70 \pm 0.03$ and $L = 0.53 \pm 0.03$.

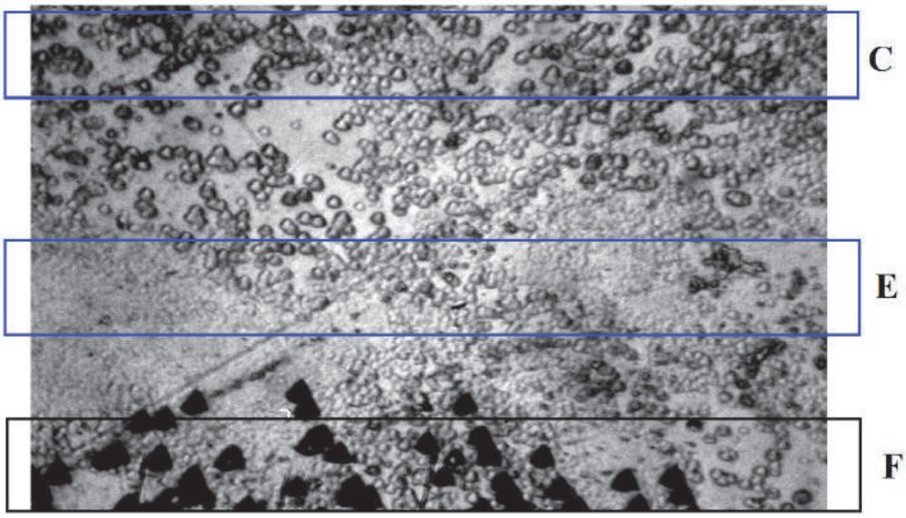


Fig. 4. The microimage of the Type 2 silicon surface at Stage 7, observed under a metallographic microscope. zone C, located far from the high dislocation density zone and from other defects (F), displays white grains (curls) with a uniform structure – both in terms of grain density and distribution. In zone E the grains are mostly collapsed (destroyed)

The obtained values clearly indicate a significant change in the surface texture of crystalline silicon after MF treatment, specifically the appearance of impurities and the cessation of dislocation movement. Using X-ray spectral analysis, the chemical composition of the surface layers of the wafers in zone C, which is located far from the dislocation region (as shown in Fig. 4) was determined. The carbon content by weight percentage was found to be 8.5 %, oxygen at 0.4 %, and silicon at 91.4 % [16]. Another characteristic of the granular surface structure is its instability, as it gradually disappears, leading to a more homogeneous surface on the silicon wafers [17].

We have systematized the results of the fractal analysis in Table. A comparison of zones C, E, and F clearly reflects the structuring of the surface based on the images. The highest fractality was found in zone E ($D = 1.79$), where the impurity grains on the surface are no longer as clearly defined as in zone C. In zone E, the impurities undergo destruction and reduction in grain size, resulting in a grinding effect. The gradual leveling of the surface is also reflected in the value of lacunarity – $L = 0.54$ in zone E, compared to $L = 0.37$ in zone C.

Regarding the fractal dimension in zone F in Fig. 4, it was found to be smaller ($D = 1.7$) compared to zones C and E, which confirms that dislocations (etching pits) do not play a significant role in surface structuring relative to the appearance of impurity grains. This is also indirectly supported by the fractal data for the control samples of Type 1 without MF treatment: $D = 1.33$ and $D = 1.37$ after the first and second loadings, respectively. On the surface of the control samples, apart from dislocations, no impurities are present, so the fractal dimension is significantly smaller. At the same time, the lacunarity of the control samples (Table) – $L = 0.91$ and $L = 0.92$ after the first and second annealing and loading reflects the homogeneity of the silicon wafer surface. In contrast, the lacunarity of the MF-treated Type 2 samples is significantly reduced, even in the dislocation exit zone (zone F in Fig. 4), where it is only 0.53. These results strongly indicate that the use of fractal analysis for numerical evaluation of the silicon surface texture aligns well with the changes observed visually.

Table. Fractal dimension and lacunarity in experimental silicon samples

Figure	Stage	Dimension, *D*	Lacunarity, *L*
		Type 1	
Fig. 2 *a*	4	1.33±0,02	0.91±0.03
Fig. 2 *b*	7	1.37±0,02	0.92±0.03
		Type 2 after MF	
Fig. 3 Zone A	7	1.81±0.02	0,34±0.03
Fig. 3 Zone B	7	1.77±0.04	0.50±0.03
		Type 2 after MF	
Fig. 4 Zone C	7	1.75±0,04	0.37±0.03
Fig. 4 Zone E	7	1.79±0,04	0.54±0.03
Fig. 4 Zone F	7	1.70±0,03	0.53±0.03

The results allow to summarize the following: the use of fractal analysis proves to be an effective method for studying changes in the texture of the silicon surface under the influence of a weak magnetic field and high-temperature plastic deformation.

The fractal dimension of the surface of Type 1 (control samples without magnetic field treatment) at Stages 4 and 7 remains almost unchanged, and the movement of dislocations continues at an average speed of 0.03 μm/s. In this case, the lacunarity, at the level of $L = 0.92$, reflects the homogeneity of the surface of the silicon wafers at all stages.

The results show that the influence of a weak magnetic field is manifested in the redistribution of impurities, defects, and the atomic structure of crystalline silicon, accompanied by the segregation on the wafer surface. This changes the morphology of the surface of a single-crystal silicon wafer, altering the fractality parameters. Consequently, it becomes possible to compare the fractal dimensions and lacunarities of treated samples. A comparison of microimages and the corresponding fractal analysis of Type 1 and Type 2 samples reveals that, after holding Type 2 wafers in a magnetic field, the location of primary dislocations remains unchanged. This characterizes the magnetically induced stopping of dislocations on the surface of Type 2 samples.

Even under the influence of a weak magnetic field, stabilization or "freezing" of existing defects occurs (*e.g.*, in our case, blocking the movement of already existing dislocations in Type 2 samples). Once the field is turned off, the energy in the system is insufficient to activate these defects and initiate movement capable of causing plastic deformation and forming new dislocations. This behaviour suggests that processing silicon samples in a magnetic field can be used to obtain defect-free silicon structures.

Impurities are always present in the initial silicon samples from the wafer manufacturing process. Oxygen atoms are incorporated into CZ silicon crystals due to the reaction between the silicon melt and the quartz crucible at the crystal-melt interface. Carbon enters the silicon crystals during the growth process, originating from the polycrystalline starting material and from graphite parts of the equipment [10, 14]. This happens for both Type 1 and Type 2 samples.

In Fig. 2 *b*, for Type 1 samples, we observed that at Stage 7, the etching pits (large triangle), formed by dislocation detachment, are healed and filled by the release of atoms to the surface. In Fig. 3 *b*, for Type 2 samples, at Stage 7, we saw white grains with a uniform structure appearing on the wafer surface. Upon closer inspection, it becomes clear that some of these grains have a pyramidal shape. According to other authors, impurities, primarily hydrogen, often take on the form of pyramids that eventually collapse over time [17]. Some of the impurities brought to the surface under the influence of the magnetic field are adsorbed from the surrounding air, while others result from the segregation of impurities from within the silicon itself.

Our last discussion concerned the importance of the surface texture of crystalline silicon, which can vary and significantly depends on the growth method. The effect of surface texture on the properties of silicon-based materials has been demonstrated in biochips with fluorescence [2], using biomolecules [13], in changes to electronic properties [9], *etc*. As we can see, processing silicon samples alters the texture of the surface layers and can be used to obtain different silicon structures for practical applications [18].

CONCLUSION

The study of changes in the texture of the silicon surface under the influence of a weak magnetic field and high-temperature plastic deformation can be effectively conducted using fractal analysis of surface images. The shape, location, and number of etching pits provide valuable information about the state of a silicon material during operation, orientation of the dislocation line relative to the surface.

MF treatment leads to a redistribution of the atomic structure of crystalline silicon, along with the segregation of atoms on the surface of the plate, resulting in the formation of a granular structure. Under these conditions, the fractal dimension of the surface increases, while the lacunarity decreases. However, the lacunarity can provide additional information about the surface texture if impurity defects collapse, smoothing the surface.

When exposed to a weak magnetic field, stabilization or blocking of the movement of existing dislocations is observed. After the field is turned off, the energy in the system remains insufficient to activate these defects and initiate movement, even after subsequent annealing and loading. This behaviour suggests that processing silicon samples in a magnetic field can be a promising method for obtaining defect-free silicon structures.

Оцінка зміни текстури поверхні кремнію під дією магнітного поля та високотемпературної пластичної деформації за допомогою фрактального аналізу

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Матеріали на основі кремнію знаходять широке застосування в енергетиці, електронних пристроях та сонячних елементах, оптоелектричній та електронній промисловості. Актуальною проблемою є контрольоване використання цих матеріалів в технологіях за наявності механічних навантажень, опромінення і магнітних полів (МП).

Мета роботи полягає у дослідженні зміни текстури поверхні кремнію під дією магнітного поля та високотемпературної пластичної деформації за допомогою фрактального аналізу.

Матеріалом дослідження слугували пластинки монокристалічного кремнію n-Si, вирощені методом Чохральського (Si-CZ), і на поверхні яких було нанесено контрольоване пошкодження за допомогою алмазного індентора. У роботі застосовано метод вивчення руху дислокацій у монокристалах кремнію під дією високотемпературної пластичної деформації. Техніка експерименту поєднує кілька методів матеріалознавства: деформацію за методом чотириопорного вигину, відпал, хімічне травлення та мікроскопію. Поряд з високотемпературною пластичною деформацією здійснювалася обробка кремнію в магнітному полі. Дослідний зразок розташовували між полюсами електромагніта для створення магнітного поля. Вектор магнітної індукції був перпендикулярний нанесеній подряпині.

Техніка аналізу і опису поєднує візуальне спостереження та фрактальний аналіз мікрозображень хімічно протравленої поверхні кремнію. В рамках фрактального аналізу визначались показники фрактальної розмірності та лакунарності, які вказують на нерівномірність та складність текстури поверхні пластин. На отриманих зображеннях було видно численні виходи дислокацій на поверхню, які розташовані в околі штучно створеної подряпини, та зміни текстури поверхні.

Магнітна обробка приводить до сегрегації атомів кремнію та домішок і утворення зернистої текстури на поверхні пластини, фрактальність поверхі зразків в такому разі збільшується, а лакунарність зменшується. Показано, що під дією слабкого магнітного поля можлива стабілізація або блокування руху вже існуючих дислокацій. Після відключення поля енергія в системі недостатня, щоб ці дефекти активувалися та почали рух навіть після другого відпалу і навантаження. Така поведінка дає змогу використовувати обробку зразків кремнію в МП для отримання бездефектних кремнієвих структур.

***Ключові слова**: монокристалічний кремній, енергетика, технологія мікроелектроніки, текстура поверхні для біочипів, магнітне поле, високотемпературна деформація, ямки травлення, дислокації, фрактальний аналіз, домішки, мікрозображення*

REFERENCES

1. Siffert P., Krimmel E.F. *Silicon: Evolution and Future of a technology*. (Berlin, New York: Imprint, Springer, 2004).
2. Oillic C., Mur P., Blanquet E., Delapierre G. Vinet F., Billon T. Silicon nanostructures for DNA biochip applications. *Mater. Sci. Eng. C*. 2007. **27**(5–8): 1500.
3. Erwin S.C., Himpsel F.J. Intrinsic magnetism at silicon surfaces. *Nat. Commun*. 2010. **1**(58): 1.
4. Moritz D.C., Calvet W., Zare Pour M.A., Paszuk A., Mayer T., Hannappel T., Hofmann J.P., Jaegermann W. Dangling Bond Defects on Si Surfaces and TheirConsequences on Energy Band Diagrams: From a Photoelectrochemical Perspective. *Solar RRL*. 2023. **7**(9): 2201063.
5. Pavlyk B.V., Slobodzyan D.P., Lys R.M., Kushlyk M.O., Didyk R.I., Shykorjak J.A. Magnetically stimulated changes in the electrophysical properties of the near-surface silicon layer. *Journal of Physical Studies*. 2020. **24**(3): 3702.
6. Molotskii M. Work hardening of crystals in a magnetic field. *Philos. Mag. Lett.* 1996. **73**(1): 11.
7. Brodovoy A.V., Brodovoy V.A., Skryshevsky V.A. Influence of magnetic field on structural defects in Si and GaAs. *Appl. Surf. Sci*. 2004. **225**(1–4): 170.
8. Vladimirova T.P., Kyslovs'kyy Ye.M., Molodkin V.B., Olikhovskii S.I., Koplak O.V., Kochelab E.V. Transformations of microdefect structure in silicon crystals under the influence of weak magnetic field. *Semicond. Phys. Quantum Electron. Optoelectron.* 2011. **14**(4): 470.
9. Kukurudziak M.S. Method of "cleaning" the surface of responsive elements of silicon p-i-n photodiodes from dislocations. *Him. Fiz. Tehnol. Poverhni*. 2023. **14** (2): 182. [in Ukrainian].
10. Pavlovskyy Yu.O, Berbets O.V., Litovchenko P.G. Influence of Growth Impurities on Thermal Defect Formation in Monocrystalline Silicon. *Phys. Chem. Solid State*. 2021. **22**(3): 437. [in Ukrainian].
11. Berenschot E.J.W., Jansen H.V., Tas N.R. Fabrication of 3D fractal structures using nanoscale anisotropic etching of single crystalline silicon. *J. Micromech. Microeng.* 2013. **23**: 055024-1.
12. Jurecka S., Angermann H., Kobayashi H., Takahashi M., Pincík E. Multifractal analysis of textured silicon surfaces. *Appl. Surf. Sci*. 2014. **301**: 41.
13. Marynchenko L.V., Nizhelska O.I., Shirinyan A.S., Gorchakova N.O. Evaluation the interaction between silicon surface and microorganisms in various solvents under the influence of a static magnetic field using fractal analysis. *Innovative Biosyst. Bioeng*. 2024. **8**(2): 69.
14. Wang L., Liu J., Li Y., Wei G., Li Q., Fan Z., Liu H., An Y., Liu C., Li J., Fu Y., Liu Q., He D. Dislocations in Crystalline Silicon Solar Cells. *Adv. Energy Sustainability Res.* 2024. **5**(2): 2300240.
15. ASTM International. C 1211–02. Standard Test Method for Flexural Strength of Advanced Ceramics at Elevated Temperatures.
16. Makara V.A., Steblenko L.P., Korotchenkov O.A., Nadtochiy A.B., Kalinichenko D.V., Kuryliuk A.M., Kobzar Yu.L., Krit O.M. Magnetic-Field-Stimulated Modification of Surface Charge and Defect Content in Silicon for Solar Energy Storage. *Metallofiz. Noveishie Tekhnol.* 2014. **36**(2): 189.
17. Chu A.K., Wang J.S., Tsai Z.Y., Lee C.K. A simple and cost-effective approach for fabricating pyramids on crystalline silicon wafers. *Sol. Energy Mater. Sol. Cells*. 2009. **93**(8): 1276.
18. Wang J., Sun B., Zhu Z. Biochip Systems for Intelligence and Integration. *Systems*. 2023, **11**(1): 43.

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