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RESEARCH ARTICLE

Influence of Local Mechanical Stress on Mono- and Polycrystalline Silicon-Based p-n Junction Under Illumination

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ABSTRACT In this article, the effect of local mechanical stress on the properties of monocrystalline and polycrystalline silicon-based p-n junctions under illumination is studied and analyzed experimentally and theoretically. Results from the experiments showed that when the local mechanical force was increased from 4 N to 20 N, the short-circuit current of the monocrystalline silicon-based p-n junction changed nonlinearly from 24 mA to 43 mA, and that of the polycrystalline silicon-based p-n junction changed linearly from 14.7 mA to 16.7 mA. Experimental results shows that the ideality coefficient of the p-n junction based on monocrystalline silicon decreased from 1.274 to 0.807 and that of polycrystalline from 1.274 to 1.102. Therefore, when the mechanical force applied on monocrystalline silicon increased, the dominant recombination changed from Shockley-Read-Hall to Auger. On the other hand, in polycrystalline silicon, the dominant Shockley-Read-Hall recombination did not change due to the grain boundaries. So, it means that mechanical force causes the narrowing of the band gap of the silicon not increasing of number of recombination centers. When mechanical force increases from 4 N to 12 N, fill factor of monocrystalline increased by 5.75% and that of polycrystalline decrease by 1.1%. In the range of 4 N and 20 N mechanical force, saturation current of monocrystalline and polycrystalline silicon p-n junction changed from 8 μA to 41 μA. and 22 μA to 97 μA, respectively.

INDEX TERMS Numerical simulation, p-n junctions, silicon, stress, sensors.

I. INTRODUCTION

When dopant atoms are introduced into silicon, its electrical conductivity changes dramatically depending on the type of dopant atom. This also leads to changes in the silicon band structure, including a narrowing of its band gap and changes in the kinetic parameters of the carriers such as lifetime, diffusion length and mobility. Adding group 3 or 5 elements to a silicon creates p-type or n-type conductivity. Such action is identified as doping in semiconductor production and is utilized in the production of many *p-n* junction semiconductor devices such as diode, transistor, semiconductor capacitor, and solar cell [1]. Doping concentration can be determined by analyzing scanning electron microscope (SEM) images using Monte Carlo method [2]. Measuring of doping concentration of metal-semiconductor junction region is difficult due to metal contamination of semiconductor [3]. Various methods were developed to identify the most accurate doping profile in semiconductors [4]. When a p-n junction is created in a silicon-based *semiconductor crystal* the latter can serve as a simple rectifier diode or solar cell. Although the p-n junction was discovered in 1939, research is still being conducted [5] to explore the wide range of potential applications of *p-n* junctions.

Mechanical stress has direct impact on the properties of silicon, such aspect was extensively studied in the literature [6]. When a mechanical force is applied to centrosymmetric semiconductor, a flexoelectric phenomenon is created resulting from polarization and gradient stress on silicon crystal [7]. Although, the magnitude of the flexoelectric effect in crystals

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is very low, the main scientific research [8] has been devoted to understand nanoscale crystals with high mechanical stress since the flexoelectric effect is inversely proportional to the size. Another phenomenon witnessed on nanoscale crystals is the flexo-photovoltaic effect [9]. Such phenomenon appears when a local mechanical stress is applied to a semiconductor crystal through illumination process, such phenomenon was observed experimentally [10] and theoretically [11]. Both theoretical and experimental evidence support the idea that mechanical stress can cause silicon to become a direct semiconductor [12] and that it can be used to make light-emitting diodes [13]. Hence, as silicon-based *p-n* junction is affected by mechanical stress, its properties can change. The influence of mechanical stress on the characteristics of silicon-based *p-n* junction in diode mode was studied by Wortman, who found that the current of the *p-n* junction increases sharply when the value of mechanical stress is higher than 10^5 N/cm^2 [14]. However, the effect of mechanical force on the illuminated *p-n* junction is poorly investigated.

When a mechanical stress is applied to an illuminated crystalline silicon, a flexo-photovoltaic effect can be created [12], thereby converting light energy into electrical energy in a semiconductor without a *p-n* junction [12]. A photocurrent results from such photovoltaic effect that increases up to 100 times when the mechanical stress increases. Also, applying a mechanical stress to a silicon-based *p-n* junction diode can form a piezo-junction [15] that is utilized in making mechanical sensors [16] which sensitivity is limited due to the noise generated in the diode [17].

Based on literature review, effect of mechanical stress on illuminated monocrystalline silicon and p-n junction in diode mode were well studied. But, the effect of mechanical stress on illuminated p-n junction has not been studied yet. So, we decided to study the effect of mechanical stress on illuminated mono- and polycrystalline silicon p-n junctions. Because, according to our expectations, monocrystalline or polycrystalline silicon p-n junction can be used as a photo-mechanical sensor to use as a scales. Besides, mechanical stress can increase or decrease the photocurrent of silicon p-n junction. So, it is important to do experiment to find the increasing or decreasing of photocurrent and prove scientifically the phenomenon appeared when mechanical stress applied on silicon p- junction.

II. MATERIALS AND METHODS

In this scientific work, the simultaneous effect of local mechanical stress and illumination on silicon-based *p-n* junction was investigated. Both poly- and monocrystalline silicon-based *p-n* junctions were selected as samples. To increase the optical sensitivity of the *p-n* junction, its surface was coated with 75 nm thick SiN_x as an anti-reflection layer. SiN_x is also widely used in the surface coating of silicon-based solar cells [18]. The Average refractive index is 1.96, which is the most ideal value for anti-reflective materials used to cover the surface of silicon-based solar cells. According to Fresnel's laws, the reflection coefficient of the interface of silicon and air is approximately 38% [19]. However, if 75 nm thick SiN_x is placed between air and silicon, the reflection coefficient is reduced to 10%. As a result, covering the surface of silicon-based *p-n* junction with SiN_x, increases its optical sensitivity by 28%. Thus, the SiN_x/*n*-Si/*p*-Si structure was analyzed in this research. Phosphorus atoms with a concentration of 1e17 cm^{-3} and Boron atoms with a concentration of 1e15 cm^{-3} were doped in the emitter and base regions. The thickness of the emitter layer is 1 μm and the thickness of the base is 174 μm.

A newly developed system based on Sinton Sunc-Voc, illustrated in Figure 1, has been developed to apply local mechanical stress to a silicon-based *p-n* junction and illuminate it at the same time. The system offers the advantage of precise control over the local mechanical force applied to the p-n junction, with an accuracy of 0.05 N. The needle (8) serves as a front contact, enabling the measurement of the current and voltage generated upon illumination of the sample. The sample's back is covered with a solid aluminum (4) and the current from the rear contact is transmitted to the probes through a copper base (5). Diameter of needle is 100 μm. The light source used is a lamp with a spectrum close to the AM1.5G spectrum. The light coming from the lamp is directed through the slit, producing a beam of an adequate radius that illuminates only the portion of the sample subjected to mechanical stress. Area of sample is 1 cm^2. Whole area of sample is illuminated using light of Xenon lamp with 1 suns intensity. Spectrum of Xenon lamp is close to spectrum of natural light.

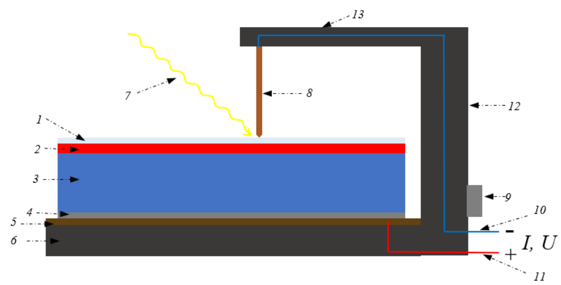

FIGURE 1. System for experimenting of effect of local mechanical stress on p-n junction: 1 – optic layer, 2 – n region, 3 – base, 4-rear contact, 5-copper substrate, 6-stand, 7-ray, 8-copper needle, 9-hoist 10-negative probe, 11- positive probe, 12-stake, 13-needle holder.

A Sinton Suns-V_{oc} device was used to determine the voltage generated at the *p-n* junction as a function of light intensity.

Although our work primarily focuses on experimental investigation, we employed the least square method to analyze the collected data and derive a mathematical function describing the relationship between short circuit current and mechanical force. The least square method enabled us to fit a curve to the experimental data, allowing us to quantify the underlying relationship accurately. These findings support the experimental results and provide further insight into the relationship between short circuit current and mechanical force.

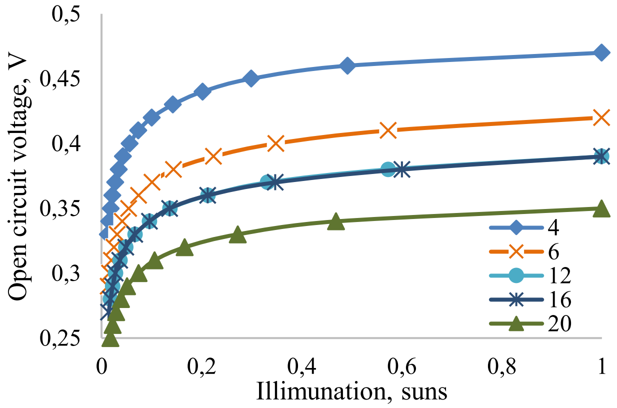

FIGURE 2. Dependence of open circuit voltage of polycrystalline silicon-based p-n junction on light intensity under various mechanical forces.

III. RESULTS AND DISCUSSION

When the solar cell is illuminated and applied mechanical force, shadow will appear due to copper needle. It is difficult to avoid shadowing of mechanical stressed surface. We imagined that mechanical stress changes the properties of silicon such as band gap, recombination rate, charge carrier mobility and carrier lifetime. When silicon p-n junction is illuminated, charge carriers are generated and transport to contacts due to internal electric field. If illuminate the whole area of silicon p-n junction is illuminated and applied mechanical stress at the same time and comparing the results of stress applied as well as unstressed samples, we have to chance to evaluate effect of mechanical stress on device performance. Scientifically, mechanical stress is varied depending on depth. It makes more difficult the evaluation of the effect of the mechanical force. In our future work, we aim to study the effect of uniaxial mechanical force on properties of silicon using computational material science methods and properties of device using numerical simulation. In this work we tried to give experimental results and their scientific discussions.

Figure 2 shows the relationship between the open circuit voltage of the polycrystalline silicon-based *p-n* junction and the light intensity when subjected to local mechanical stress ranging from 0.4 N to 2 N. It was observed that as the applied mechanical force increased, the dependence of the open circuit voltage on the light intensity remained qualitatively unchanged, but decreased quantitatively to 0.075 V/N depending on the value of applied force. Hence, there is an effect of the local mechanical force on the photoelectric parameters of the silicon-based *p-n* junction. The number of defects and recombination is a reflection of the dependence of open circuit voltage generated in the *p-n* junction on the light intensity. Polycrystalline silicon is a complex system consisting of small crystals of different sizes and isotropic properties [20]. When a silicon-based *p-n* junction is affected by mechanical force, its band structure can change and new recombination centers can be formed. Increasing of carrier concentration can be identified using various techniques [21]. It helps to differentiate the effects of decreasing band gap and forming recombination centers. The voltage can change due to an increase in the number of recombination centers and due to a change in the band structure. In polycrystalline silicon, the concentration of recombination centers formed due to grain boundaries is high, therefore, under the influence of local mechanical force, the change of the main photoelectric parameters of polycrystalline silicon-based *p-n* junction can cause a change in the band structure or a change in the concentration of recombination centers. Therefore, it is impossible to make a correct assessment. To address this challenge, the impact of local mechanical stress on both poly- and monocrystalline silicon-based *p-n* junctions was studied. Monocrystalline silicon does not have grain boundaries, and therefore the concentration of recombination centers caused by dislocations is about 7000 cm^{-2} [22].

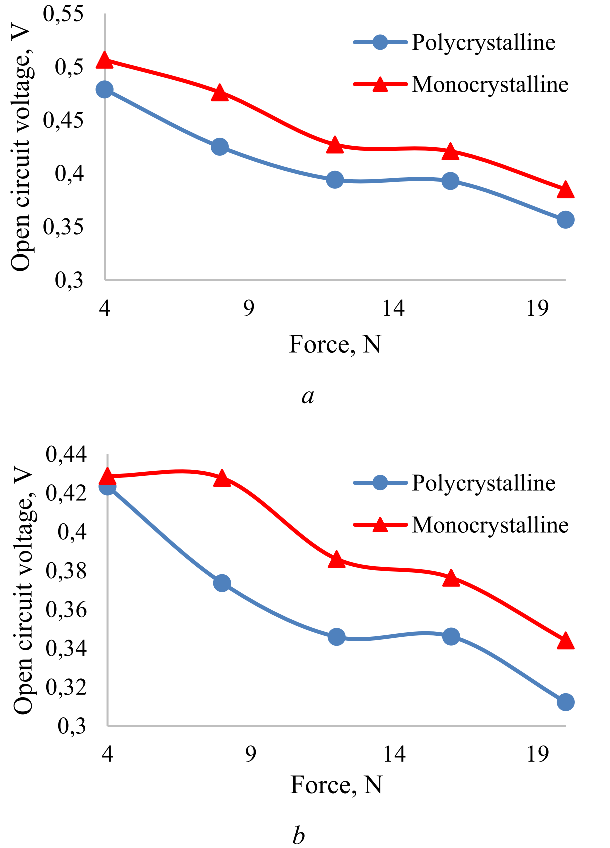

FIGURE 3. Dependence of the open circuit voltage of the polycrystalline and monocrystalline silicon-based p-n junction illuminated with light intensity of 1 sun (a) and 0.1 sun (b) on the local mechanical force.

Figure 3 shows the dependence of the open circuit voltage of polycrystalline and monocrystalline silicon *p-n* junctions illuminated with light intensity of 1 sun (a) and 0.1 sun (b) on local mechanical force.

The quality of the change of the open circuit voltage depending on the mechanical force when the sun is illuminated with 1 sun is almost the same for a monocrystalline and polycrystalline silicon-based *p-n* junctions. When the light intensity was 0.1 sun, the dependence of the open circuit voltage on the local mechanical force was different for monocrystalline and polycrystalline silicon-based *p-n* junctions. This difference is likely due to the lower concentration

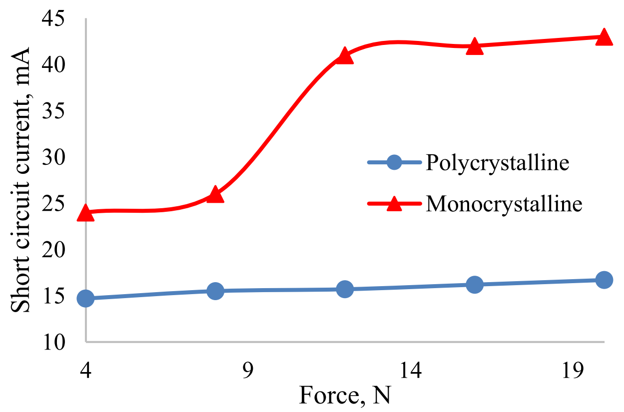

FIGURE 4. Dependence of the short-circuit current of polycrystalline and monocrystalline silicon-based p-n junction on the local mechanical force.

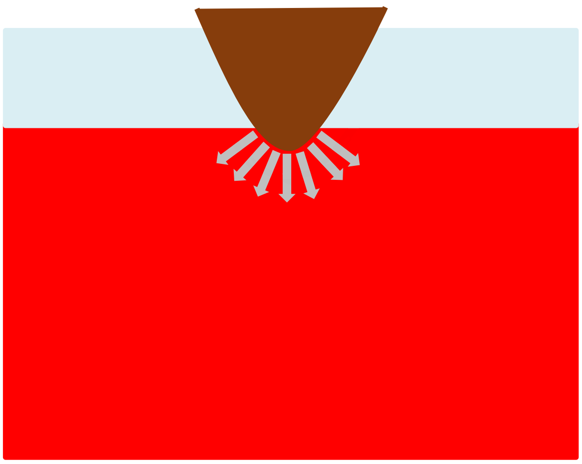

FIGURE 5. The directions of influence of the mechanical stress around the needle when mechanical force is applied to the sample.

of photogenerated charge carriers under low light conditions. This helps to evaluate the effect of mechanical force on the *p-n* junction.

It was assumed that the changing of concentration of recombination centers and band structure of material changes when a silicon-based *p-n* junction is affected by mechanical force. As the concentration of recombination centers increases, the rate of Shockley-Read-Hall recombination also increases [23]. This should have caused the short circuit current to decrease. However, according to the dependence of the short-circuit current on the polycrystalline and monocrystalline silicon-based *p-n* junction shown in Figure 4, it was found that the short-circuit current increases when the value of the mechanical stress increases. This negates the increase in recombination center concentration. Accordingly, the local mechanical force mainly affects the band structure of the material. As a result, when the local mechanical force increased from 4 N to 20 N, the short-circuit current of monocrystalline silicon-based *p-n* junction changed from 24 mA to 43 mA, while that of the polycrystalline silicon-based *p-n* junction changed from 14.7 mA to 16.7 mA. According to our theoretical studies, the dependence of the short-circuit current generated in the *p-n* junction on the mechanical stress can be calculated by using formula 1.

In this theoretical study, the impact of mechanical stress on the band structure of silicon was taken into account. As a result of the elevated rate of recombination in polycrystalline silicon, its short-circuit current is lower compared to that of monocrystalline silicon.

$$I_{sc} = I_{sc,o} + \frac{\beta\gamma}{\sqrt{Akq^2}}\sqrt{F_k} \tag{1}$$

Here: A, β, γ – constants, F_k - applied mechanical force, q – electron charge, k – Boltzmann constant, I_{sc} – short circuit current.

Under the influence of mechanical force, the short-circuit current of the monocrystalline silicon-based p-n junction exhibited a steep, nonlinear increase, while that of the polycrystalline silicon-based p-n junction showed a linear increase. In addition, when the light intensity was changed from 0.1 sun to 1 sun, the dependence of open circuit voltage on mechanical force changed for monocrystalline silicon-based p-n junction, but remained unchanged for the polycrystalline one. This is because polycrystalline silicon is isotropic and monocrystalline silicon is anisotropic. When a local mechanical force is applied to the p-n junction through the needle, the mechanical force spreads in different directions as shown in figure 5.

In the experiment, it was found that there is an effect of mechanical force on the band structure of silicon. The nth energy level in silicon is a function of the wave vector. When the crystal is stressed, the nth energy level will depend on the mechanical stress along with the wave vector. The changing of nth energy level due to mechanical stress is calculated using formula 2.

$$\Delta E^{(n)}(k, \varepsilon_{ik}) = E^{(n)}(k, \varepsilon_{ik}) - E_0^{(n)}(k) = \sum_{i,j} D_{ij}^{(n)}\varepsilon_{ij} \tag{2}$$

Here: k – wave vector, ε_{ik} – deformation tensor, $D_{ij}^{(n)}$ – deformation potential $E_0^{(n)}(k)$ – n^{th} level energy of silicon, $E^{(n)}(k,\varepsilon_{ik})$ – n^{th} level energy of silicon under mechanical stress.

Monocrystalline silicon is anisotropic, and the effect of mechanical stress depends on the direction of the crystal. Therefore, the effect of mechanical stress on monocrystalline silicon is represented by the strain tensor. Polycrystalline silicon is isotropic [24], that is, the effect of mechanical stress on it does not depend on the direction. Since the polycrystal consists of small single crystals, the orientation of the crystals is determined by probability. A monocrystal has three main orientations [111], [110], and [100] independent of each other. In this scientific work, a p-n junction based on monocrystalline silicon with [100] orientation was studied. The polycrystalline silicon sample is equally likely to be in [111], [110] and [100] orientations. Since monocrystalline silicon was grown in the [100] direction, the mechanical stress was applied along this direction. The change in the valence band of monocrystalline silicon due to mechanical stress is calculated using formula 3. The maximum energy of the valence band of silicon corresponds to the value of the wave vector k=0. According to the theory of dependence of energy on the wave vector, the energy levels of the valence band of silicon in the Brillouin zone consist of parabolic functions. When subjected to mechanical stress, the peak value of these parabolas does not shift along the k axis, only the width of the parabola changes.

$$\Delta E_v = a\left(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}\right) \pm \frac{Bb}{3\sqrt{B^2k^4+C^2\left(k_1^2k_2^2+k_1^2k_3^2+k_2^2k_3^2\right)}} \times \left(3k_z^2-k^2\right)\left(\varepsilon_{33}-\varepsilon_{11}\right) \quad (3)$$

Here: B, a, b and C – deformation constants depending on type of material E_v – valence band energy.

When mechanical stress is not applied, the conduction band of the silicon is minimum at the value of $k=0.8k_{max}$ wave vector. If a mechanical stress is applied, the minimum of conduction band shifts to the edge of Brillouin zone along the axis of the wave vector in addition to the change in the energy of the conduction band. That is, the difference between the wave vectors of the maximum energy of the valence band and the minimum energy of the conduction band increases when mechanical stress is applied, and decreases when mechanical strain is applied. Therefore, when mechanical stress is applied to silicon, it has been found that the band structure transit indirect to [25]. Formula 4 calculates the change in the minimum energy of the conduction band when mechanical stress is applied to monocrystalline silicon with [100] orientation. When a mechanical stress is applied, the change of the valence and conduction band causes change of the band gap, the Fermi level, and the concentration of charge carriers. Because they are interdependent parameters.

$$\Delta E_c = D_{11}\left(\varepsilon_{22}+\varepsilon_{33}\right)+D_{33}\varepsilon_{11} \quad (4)$$

Here: E_c – conduction band energy

According to the result given in Figure 3, it was found that the band gap of silicon is narrowing. The narrowing of the band gap can be expressed by changing the maximum energy of the valence band and the minimum energy of the conduction band. Formula 5 shows the change in bandgap of silicon applied mechanical stress along the [100] axis.

$$\Delta E_g = \left(a-\Xi_u\right)\left(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}\right)-\Xi_d\varepsilon_{33}+b\left|\varepsilon_{33}-\varepsilon_{11}\right| \quad (5)$$

Here: Ξ_u and Ξ_d – constant of deformation potential.

Constants of deformation potential were determined for silicon in experiment: a=-3.9eV, b=-1.36 eV [26], Ξ_u=8.5eV and Ξ_d=-5.2eV [27]. By using those parameters, decreasing of band gap by 0.075 eV was found that when a force of 1000 N is applied to the surface of monocrystalline silicon with 0.01 cm^2 area.

When the difference between the wave vectors of the extreme points of the valence and conduction bands increases, the concentration of phonons increases. An increase in the concentration of phonons causes an increasing of the probability of electron-phonon scattering and decreasing of the mobility of charge carriers [28]. Fig. 6 shows experimentally determined dependence of the lifetime of minority charge carriers formed in the monocrystalline and polycrystalline silicon-based *p-n* junction on mechanical force. When the mechanical stress increased, the mobility of charge carriers decreased and therefore the lifetime of minority charge carriers also decreased. Because the lifetime of charge carriers is directly proportional to their mobility [29]. In addition, the change in the energy of the conduction band affects the mobility of electrons and the change in the energy of the valence band affects the mobility of holes.

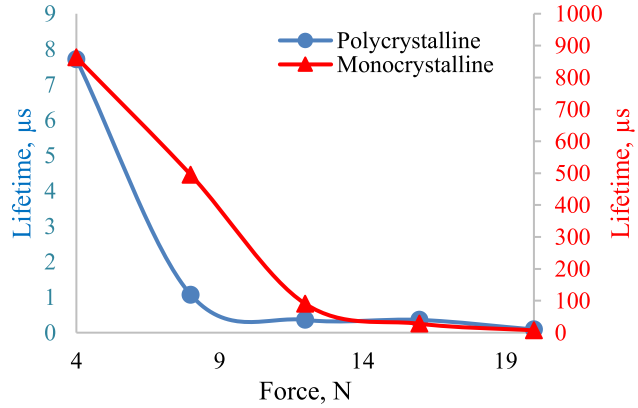

FIGURE 6. Dependence of minority carriers lifetime of polycrystalline and monocrystalline silicon based p-n junction on local mechanical force.

It is possible to determine the quality of the *p-n* junction, the change of shunt and series resistances using the fill factor. Figure 7 shows the dependence of the fill factor of monocrystalline and polycrystalline silicon-based *p-n* junctions on local mechanical force. Ideally, the shunt resistance should be as large as possible and the series resistance as small as possible to maximize the output power and the fill factor of the *p-n* junction in photovoltaic mode. Increasing the mechanical force increased from 4 N to 12 N increased the fill factor of a monocrystalline silicon-based p-n junction by 5.75% due to a decrease in series resistance. However, increasing the force from 12 N to 20 N resulted in a 1.23% decrease in fill factor because the shunt resistance decreased at a faster rate than the series resistance as the needle approached the *p-n* junction. Polycrystalline silicon is composed of small single crystals and it is isotropic. To calculate the total shunt resistance in polycrystalline silicon, the specific resistances of each grain are added according to the exact law. When a mechanical force affects the polycrystalline silicon-based *p-n* junction, the grains are strained in the direction of the force and expand in the plane perpendicular to the force. In the *p-n* junction, the internal electric field is also created in the direction of the mechanical force. Therefore, charge carriers also move in the direction of the force. Therefore, under the influence of mechanical force, the surface of grains perpendicular to the current increases and their length decreases. The resistance is inversely proportional to the length of the electrical conduc-

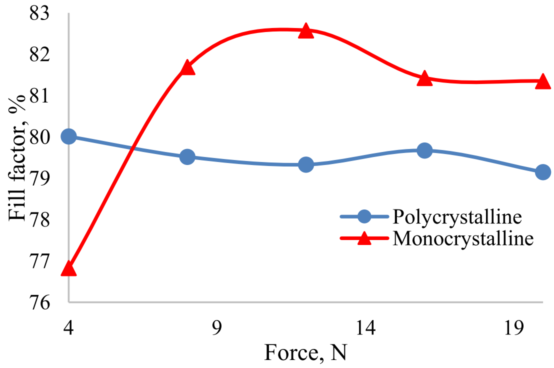

FIGURE 7. The dependence of the fill factor of polycrystalline and monocrystalline silicon-based p-n junctions on the local mechanical force.

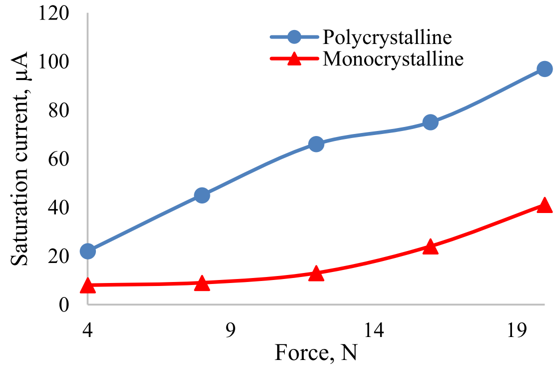

FIGURE 8. The dependence of the saturation current of polycrystalline and monocrystalline silicon-based p-n junctions on the local mechanical force.

tor. Accordingly, the resistance of each grain decreases under the influence of mechanical force. The shunt resistance of the polycrystalline silicon-based *p-n* junction decreases faster than the series resistance under the influence of mechanical force. The fill factor of the polycrystalline silicon-based *p-n* junction only decreased with the increase of the mechanical stress.

Mechanical force is applied for 1 hour to test changing the photoelectric parameters are transient or sustained. Fill factor, short circuit current and open circuit voltage are measured at starting of applying mechanical force and 1 minutes, 10 minutes and 1 hour after applied mechanical force. Value of photoelectric parameters change very little as fluctuation. According to this experiment, it was found that changing of photoelectric parameters are sustained not transient.

To determine the electrical properties of the p-n junction, both forward and reverse voltages should be applied to the junction in diode mode. This allows for measurement of parameters such as forward and reverse bias current, breakdown voltage, which can provide information about the behavior of the junction under different operating conditions. In p-n junction, mainly two types of currents occur: drift current and diffusion current. When the forward voltage is applied to a p-n junction, the resulting current includes both drift and diffusion currents. The drift current is due to the movement of charge carriers in response to the electric field in the junction, while the diffusion current is caused by the movement of charge carriers due to the concentration gradient of the carriers in the junction. When a reverse voltage is applied to the junction, only the diffusion current occurs, but its magnitude is typically much smaller compared to the drift current in forward. When the amount of reverse voltage applied to an ideal p-n junction is increased, the reverse current also increases, but starting from a certain value of the voltage, the amount of reverse current does not increase further and saturates. The saturation current is the main parameter in evaluating the quality of the diode and the kinetic parameters of minority charge carriers. In a real p-n junction, in most cases, the value of the reverse current increases continuously as the value of the reverse voltage increases. Reverse current of ideal p-n junction doesn't change until breakdown voltage. In real p-n junction, module of reverse current increase when module of voltage increases until breakdown voltage. After breakdown voltage, module of reverse current increase sharply. In this case, the saturation current is conditionally determined. To determine the characteristics of a real p-n junction, it is necessary to record the applied voltage and measure the resulting current.

Therefore, to determine the saturation current of a real p-n junction, it is necessary to determine the voltage at which the p-n junction reaches the saturation current. For this, the equation of the I-V characteristic of the p-n junction given in formula 6 was used.

$$I = I_s \left(\exp\left(\frac{Vq}{nkT}\right) - 1 \right) \tag{6}$$

Here: I_s – saturation current, T – absolute temperature, V – voltage and I – current, n – ideality factor

If we introduce the conditions $I = I_s$ and $n = 1$ into equation 6 and solve the equation with respect to U, the expression in formula 7 is formed.

$$V = V_T \ln(2) \tag{7}$$

Here: $V_T = \frac{kT}{q}$ - thermal voltage.

During the experiment, the temperature was 300 K, so the voltage of the conditionally reaching saturation current was −17.94 mV. The current of the samples at this voltage was conditionally accepted as the saturation current. Figure 8 shows the dependence of the saturation current of polycrystalline and monocrystalline silicon-based p-n junction on local mechanical force. When the local mechanical force increased from 4 N to 20 N, the saturation current of polycrystalline silicon-based p-n junction increased from 22 μA to 97 μA, and the saturation current of monocrystalline silicon-based p-n junction increased from 8 μA to 41 μA. As mentioned above, when the mechanical strength increases, it mainly affects the band structure. Similarly, when mechanical force is applied to silicon, the decreasing of the open circuit voltage and the increasing of the short-circuit current prove the narrowing of the bandgap. As the band gap narrows, the concentration of minority charge carriers increases and therefore the saturation current also increases.

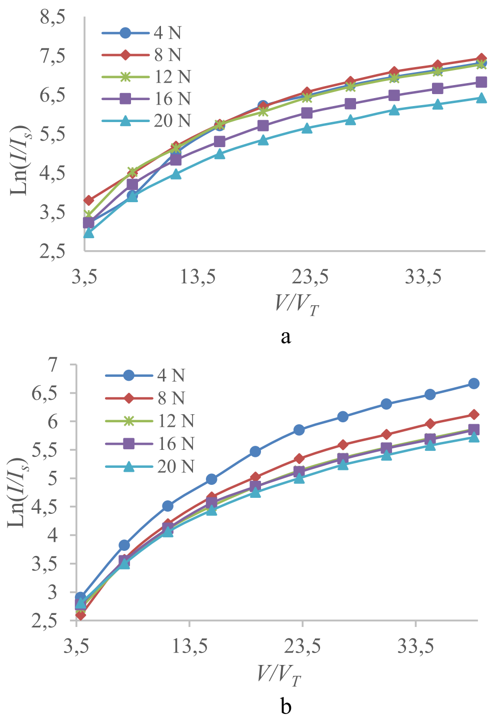

FIGURE 9. Forward I-V characteristics of monocrystalline (a) and polycrystalline (b) silicon-based p-n junction on a semi-logarithmic scale.

According to formula 8, the saturation current density of the *p-n* junction is directly proportional to the concentration of charge carriers, but inversely proportional to their lifetime. According to the results given in Figure 6, the lifetime of minority charge carriers decreased when the mechanical stress increased. Therefore, the saturation current increased under the influence of mechanical stress.

$$J_S = (ekT)^{\frac{1}{2}} n_i^2 \left[\frac{1}{n_n}\sqrt{\frac{\mu_n}{\tau_n}} + \frac{1}{p_p}\sqrt{\frac{\mu_p}{\tau_p}} \right] \quad (8)$$

Here: n_i – intrinsic carrier concentration, n_n and p_p – concentration of electron and holes, μ_n and μ_p – mobility of electron and holes, τ_n and τ_p – lifetime of electron and holes.

If we logarithm the both side of equation 6 we get the logarithmic relationship between I/I_s and V/V_T as a linear equation.

$$Ln(\frac{I}{I_S}) = \frac{1}{n}\frac{V}{V_T} \quad (9)$$

The quality of the *p-n* junction can be evaluated by the dark ideality factor in in the diode mode and the light ideality factor in the photovoltaic mode [30]. Figure 9 shows the forward logarithmic I-V characteristic of a monocrystalline (a) and a polycrystalline (b) silicon-based *p-n* junctions given equation 9 on a semi-logarithmic scale. A decrease in the logarithm of the current leads to an increase in the ideality factor. Due to the effect of resistance, it is difficult to evaluate the quality of the *p-n* junction by the dark ideality coefficient. Therefore, the ideality factor increases due to the decreasing of the shunt resistance when a mechanical force is applied. Physical analysis of this result can lead to wrong conclusions.

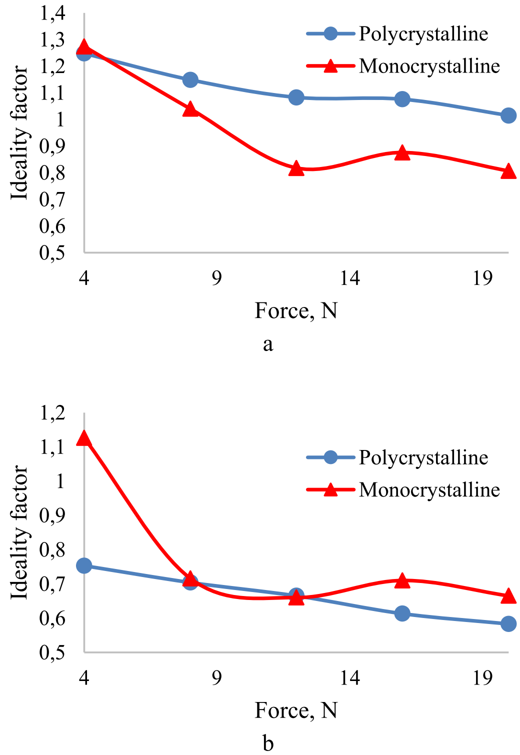

FIGURE 10. The dependence of the ideality factor of the polycrystalline and monocrystalline silicon-based p-n junctions illuminated with light intensity of 1 sun (a) and 0.1 sun (b) on the local mechanical force.

Therefore, the quality of the *p-n* junction can be estimated and physically justified by the light ideality factor determined in the Suns-V_{oc} mode.

The light ideality factor of the p-n junction is measured on a Sinton Suns-Voc device. Fig. 10 shows the dependence of the ideality factor of the polycrystalline and monocrystalline silicon-based p-n junction, under illumination with light intensity of 1 sun (a) and 0.1 sun (b), on local mechanical force. At low intensity, the ideality factor was lower than 1 for a p-n junction based on polycrystalline silicon and greater than 1 for monocrystalline silicon under a force of 4 N. At high light intensity, the ideality coefficient was greater than 1 for both polycrystalline and monocrystalline silicon-based p-n junctions. When the mechanical force increased, ideality factor decreased for both polycrystalline and monocrystalline silicon-based p-n junctions. It is possible to analyze the recombination process in the p-n junction depending on the value of the ideality factor [31]. If the ideality factor is n=1, Shockley-Read-Hall (SRH) recombination is dominant in this p-n junction and minority charge carriers play the main role, if n=2, SRH recombination in p-n junction again dominates, but both minor and major charge carriers play a main role. In a silicon-based p-n junction, the ideality factor can be less than 1, in which case Auger recombination dominates in the p-n junction. According to the results given in Figure 10.a, when the mechanical force increases from 4 N to 20 N, the ideality factor of the monocrystalline silicon-based p-n junction decreases from 1.274 to 0.807, and that of polycrystalline silicon decreases from 1.274 to 1.102.

It was determined that the dominant recombination changes from SRH to Auger when a mechanical force affects the p-n junction based on monocrystalline silicon. In monocrystalline silicon p-n junction, ideality factor of p-n junction shows that effect of decreasing of band gap has a more effect on short circuit current than increasing of recombination centers. Because the concentration of charge carriers increased when mechanical stress was applied to monocrystalline silicon. Increasing the concentration of charge carriers leads to increase the percentage of Auger recombination and increasing of defect concentration cause to increase the percentage of SRH recombination. However, SRH did not change as the dominant recombination in polycrystalline silicon-based p-n junction. Because the grain boundaries of polycrystalline silicon are considered defects and they create certain energy levels in the band gap. They also help maintain the dominance of SRH recombination.

IV. CONCLUSION

The effect of mechanical stress on illuminated monocrystalline and polycrystalline silicon-based *p-n* junctions was studied experimentally. The obtained results suggest that recombination centers are not formed in silicon under the influence of mechanical stress, and the physical parameters of the *p-n* junction can be changed due to the changing of band structure. In particular, it was found that short circuit current of the monocrystalline silicon-based *p-n* junction increases sharply nonlinearly when a local mechanical force is applied. Therefore, it is possible to increase the output power by applying local mechanical stress to the monocrystalline silicon-based solar cell. In this case, it will be possible to simultaneously use both photovoltaic and flexo-photovoltaic effects to convert light energy into electrical energy. That is, a photovoltaic effect is created due to the presence of a *p-n* junction in a monocrystalline silicon-based solar cell, and a flexo-photovoltaic effect is created due to the creation of a gradient stress under the influence of local mechanical stress. Accordingly, stress applied monocrystalline silicon has advantages to be used in solar cell. On the other hand, the short-circuit current of polycrystalline silicon-based p-n junction was found to have a small but linear variation depending on the local mechanical force. This is due to the fact that polycrystalline consist of grain boundaries, which prevent drastic increasing of carriers when mechanical stress is applied. Therefore, *p-n* junction based on polycrystalline silicon may be used in the production of photo-mechanical sensors. While our findings provide valuable insights into the effect of mechanical stress on illuminated silicon-based p-n junctions, it is important to note that our study did not directly investigate the changes in material properties caused by mechanical stress. To address this limitation, future research could employ advanced computational methods such as Density Functional Theory (DFT) to gain a deeper understanding of the underlying phenomena occurring within the material when subjected to mechanical force. This would enable a more comprehensive exploration of the relationship between mechanical stress, material properties, and device performance.

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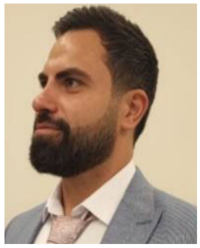

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