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Temperature dependence of solar cell characteristics through frequency noise level and ideality factor measurements

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Abstract: Temperature effects and thermally induced noise in photo detectors are significant in the detection processes. Degradation of electrical and optical characteristics of the photo detectors in the increased temperature conditions is one of the most important limitation factors for their application. Since most of the electrical processes in semiconductor devices depend, in some extent, on the temperature, investigations at temperatures higher than room temperature may reveal possible changes in output characteristics of the device. From the technological point of view, thermally induced noise increase minimum signal that can be detected, and this is especially important for the low energy and non ionizing radiation detectors, since the noise level presents the major performance limitation. In this paper these effects are studied through frequency noise level measurements and measurements of the main output characteristics of solar cells.

Keywords: Temperature dependence, 1/f noise, Solar cells, Output voltage, Ideality factor

Temperaturna odvisnost lastnosti sončnih celic glede na nivo frekvenčnega šuma in meritev faktorja kvalitete

Izvleček: Temperaturni efekti in termično vzbujan šum imajo velik vpliv v procesu razpoznavanja v fotodetektorjih. Degradacija električnih in optičnih lastnosti fotodetektorjev pri povišani temperaturi je eden izmed najpomembnejših omejitvenih faktorjev njihove uporabe. Ker je večina električnih procesov temperaturno odvisnih lahko raziskave pri temperaturah nad sobnimi razkrijejo morebitne spremembe njihovih lastnosti. Iz tehnološkega vidika termično vzbujan šum dvigne najnižji nivo signala, ki ga še lahko zaznamo, kar je še posebej pomembno pri nizkoenergijskih detektorjih ne detektorjih neionizirajočih sevanj saj nivo šuma predstavlja največjo oviro učinkovitosti. V članku so ti vplivi raziskani s strani meritev nivoja frekvenčnega šuma in glavnih izhodnih karakteristik sončnih celic.

Ključne besede: temperaturna odvisnost, 1/f šum, sončne celice, izhodna napetost, faktor kvalitete

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1. Introduction

The extensive miniaturization of the semiconductor devices based on semiconductor junctions (p-n, p-i-n, Schottky, etc.) introduces the problem of the temperature effects and thermally induced noise in such devices. Silicon solar cells belong to a wide group of semiconductor detector devises, though somewhat specific in its design (larger than most of the detectors), and that, together with the fact that they are directly exposed to the solar radiation makes them especially susceptible to the effect of the high temperature. For higher temperatures, thermal noise is dominant and significantly influences the detecting signal and output characteristics. Also, other types of noises especially frequency dependent generation-recombination noise, burst noise and 1/f noise increase with the increase of the temperature [1]. Since increased temperature influence all parts of semiconductor device, contact grid is also prone to some changes, particularly because surface effects are expected to be a major cause of 1/f noise. This is especially significant for solar cells because of their design (large surface to volume ratio), so materials for front contact grid should be carefully chosen. Silicides belong to a very promising group of materials which are of great interest both in physics of thin films and in microelectronics. Many of them have a low resistivity and good temperature stability that make them desirable for fabrication of reliable and reproducible contacts [2,3]. It is known that low frequency noise (1/f and burst noise) manifests as random fluctuation of the output current or voltage, leading to lowering of the efficiency of the device. Various experiments suggest [4-8] that the origin of this noise is fluctuation of the number of free charge carriers connected to existence of the traps located in the vicinity or directly in the junction area, or fluctuation of the mobility of charge carriers. These effects are more pronounced when the device is exposed to high temperature conditions, since in those conditions defects, surface states and impurities that act as traps for charge carriers could be in addition thermally activated [9]. It has been found [3,10] that ion implantation of As^+ ions in the formation of the silicides could improve electrical characteristics of silicides regarding their noise level.

Recently, a new type of materials, dye-sensitized solar cells (DSSCs) based on nanocrystalline high band gap oxide semiconductors receive much attention as cheap alternatives to the conventional solar cells made from low band gap semiconductors. From the standpoint of 1/f noise, it has been found [5] that some molecular species that strongly chelate to the semiconductor surface, suppress 1/f noise owing to passivation of the recombination sites. Thus in addition to sensitization, the dye adsorbed on the nanocrystallites plays a key role in mitigation of recombination. The mechanism involved seems to be the passivation of the semiconductor surface by the adsorbed dye. Passivation is also the cause that suppresses recombination in the dye-sensitized solar cells.

On the other hand, since all dynamic processes in semiconductor devices are temperature-dependent [1, 11-13], study of the variations of junction characteristic parameters (ideality factor, saturation current, etc.) due to the increased temperature is crucial. One of the most important electrical processes in junction devices is transport of the generated charge carriers across the junction. Type and temperature dependence of the transport mechanism is obtained from dark current-voltage (I-V) measurements of photo detectors. Main parameter that could be extracted from I-V data is the ideality factor (n), direct indicator of the output parameter dependence on the electrical transport properties of the junction. The non-ideal behavior of the device is reflected in the values of n greater than 1, and also in the temperature dependence of the ideality factor. This dependence is the result of the presence of different transport mechanisms that can contribute to the diode current at different temperatures. Determination of the dominant current mechanism is very difficult because the relative magnitude of these components depends on various parameters, such as density of the interface states, concentration of the impurities and defects, height of the potential barrier, device voltage, and device temperature. Even for a given system at a particular temperature rarely only one mechanism dominates the diode current over entire voltage regime. The main transport processes that could occur, even simultaneously, are thermionic emission, field emission, thermionic field emission, recombination-tunneling via interface states, minority carrier injection, and recombination [11]. Beside I-V measurements at different temperatures, measurements of the n(T) and n(V) dependence could narrow down possibilities of the dominant current component. Values of the ideality factor at different temperatures could indicate not only the transport mechanism, but indirectly, the presence and possible activation of the defects and impurities, acting as recombination and/or tunneling centers. Also, the presence of the defects in the material is considered to be the main cause of the existence of the current noise. Some types of noise in photo detectors are correlated with the presence of the excess current [11], binding optical and electrical characteristics of such devices.

Purpose of this paper is to present temperature dependence of main characteristics of solar cells in connection to the temperature dependence of 1/f noise level in silicides and ideality factor in photodiodes.

2. Methods

Due to the complexity of the subject, three types of measurements were performed in this experiment. Investigations of temperature dependence of 1/f noise in silicides were performed for TiN/Ti/Si samples. Ion implantation with As^+ ions, annealing and electrical characterization were performed on the samples. Implantation of arsenic was performed at 350 keV with the dose range between $1x10^{15}$ ions/cm^2 to $1x10^{16}$ ions/cm^2. Thermal treatment for all samples was performed at different temperatures for 20 min. The distinction of these measurements compared to other of this type is that they were based on the temperature dependence of the noise level in silicides for two temperatures: -18ºC and 50ºC. Noise level measurements were performed with the measurement equipment consisting of the multichannel analyzer ND-100, low noise pre-amplifier, and amplifier (standard ORTEC equipment). MAESTRO II code was used for automatic energy calibration.

Experimental measurements concerning solar cells were carried out on the commercially available silicon solar cells manufactured by Leybold. Current-voltage data were used for the characterization of the properties of solar cells. Temperature dependence was measured in the range from room temperature (21ºC) to slightly above 40ºC (41ºC).

For determining temperature dependence of ideality factor for commercially available p-i-n and p-n silicon photodiodes were used (all samples were produced by SIEMENS, trademarks BP 104, BPW34, BPW 43, and SFH 205). Direct bias dark I-V characteristics of the diodes were measured at four different temperatures, using standard configuration for I-V measurements (Hewlett-Packard current-voltage source, and two digital multimeters - SIMPSON and LEADER). Temperature range was in agreement with the operating/storage range supplied by manufacturer (21ºC - 83ºC). Measured I-V data were analyzed using ORIGIN program package. Diode parameters were obtained using standard and numerical fit methods with the correction due to the presence of series resistance.

Experiment was performed in well controlled laboratory conditions with combined measurement uncertainty less than 5% within all measurement procedures [14,15].

3. Results and discussion

3.1 Frequency noise level measurements

Temperature dependence of 1/f noise level was observed for this type of silicides, as could be expected. Spectra of frequency dependent noise on lower (-18ºC) and higher (50ºC) temperature are shown in Figures 1 and 2, respectively.

Not only that the assumption that higher temperature induces higher noise level was confirmed, but the essential part of this measurement is that it was observed that implantation dose used for fabrication of silicides could influence the increase of noise level. The possibility of improvement of silicide characteristics by ion implantation and thermal annealing was reported earlier [10], but primarily in connection to the radiation damage. Structural RBS analysis has shown that ion implantation did not induce redistribution of components for lower implantation doses. The spectra indicate that the entire titanium layer has interdiffused with the silicon substrate. The presence of the $TiSi_2$ and $TiSi_2$ phase in the implanted samples was observed. In all cases top TiN layer remains unaffected, but for higher doses of implantation ($1x10^{16}$ ions/cm^2) a disordered structure was registered. This corresponds to the amorphization of silicon substrate, which is moving deeper with the ion dose, showing that the physical properties of TiN/Ti/Si are influenced by the implantation. Also, it was found [2,3] that thermal treatment induces relaxation of crystal lattice and improvement of the crystal structure of the silicides.

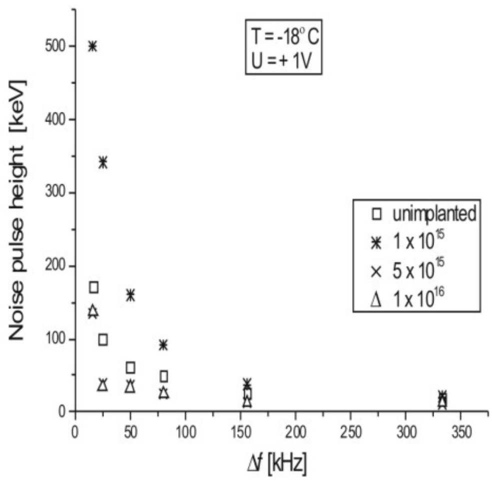

Figure 1: Frequency noise level of three implanted and one unimplanted sample at -18ºC.

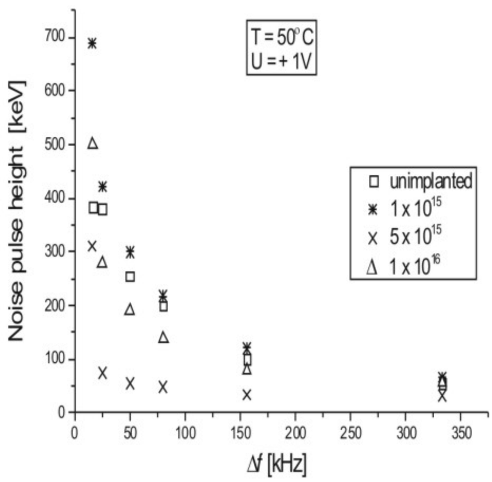

Figure 2: Frequency noise level of three implanted and one unimplanted sample at 50ºC.

However, this temperature dependent measurements indicate another very important fact that ion implantation could provide temperature stability of silicides regarding 1/f noise. Namely, from Fig. 1 and 2 could be seen that samples implanted with doses of $5x10^{15}$ions/cm^2 had lowest noise level and very good temperature stability. This could lead to an improvement of electrical characteristics of silicides and devices based on silicides as contacts (for example, solar cells).

3.2. Temperature dependence of electrical characteristics of photo detectors

Though the current transport mechanism is (theoretically) similar for most semiconducting devices based on p-n junction (for example, solar cells), the choice of the material and its structure (monocrystalline, polycrystalline or amorphous) has some influence on the transport processes. Amorphous silicon, a-Si, for example, is a direct-gap material with very high density of states within the energy gap, that could behave like recombination centers for the charge carriers. Though a-Si has high absorption coefficient and is easy to manufacture, the main difficulty in a-Si solar cell technology lies in constant decrease of efficiency during time. This effect is called Staebler – Wronski effect, and is dependent on total number of the absorbed photons, i.e., on the intensity of the light to which the cell is exposed, and the duration of the exposure.

Polycrystalline and monocrystalline solar cells are more reliable than amorphous, but inherent presence of defects and impurities in the basic material could, during time, produce some negative effects. This is specially emphasized if those states are located within the energy gap and are activated during work due to the temperature increase, for example. In such a case they become traps for optically produced electron-hole pairs, and thus decrease the number of collected charge carriers. Macroscopically, this effect could be observed as a decrease of the output current and voltage, and ultimately could lead to the decrease of the efficiency of solar cell.
When the temperature dependence of solar cell characteristics is concerned, although an increase of the current with the temperature increase was observed, main output characteristics such as efficiency were negatively influenced by high temperature. This is due to the fact that open circuit voltage rapidly decreases with an increase of the temperature, as could be seen in Fig. 3.

The rate of the decrease ($\Delta V_{oc}/\Delta T$) for this particular cell was -2,48mV/°C (using linear approximation method), and that made it particularly temperature sensitive. This could be the result of the dependence of the V_{oc} on the dark current J_0 of the cell. Namely, decrease of V_{oc} with an increase of J_0 is connected to the dominating transport mechanisms of the device, and since increased temperature unavoidably leads to the increase of J_0, the decrease of V_{oc} is expected. Also, because of the working conditions of solar cells (direct exposure to the solar radiation), their temperature increases very rapidly (up to 40°C in the first 2-3 minutes of work), so better temperature stabilization of characteristics, and/or adequate cooling are main requirements for suc-

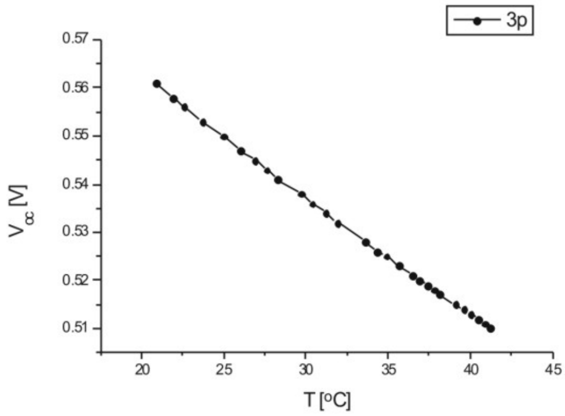

Figure 3: Temperature dependence of open circuit voltage V_{oc}.

cessful and long-term operation of solar systems. Also, voltage decrease in the maximum power point (P_m) has great influence on the efficiency. One of the main reasons for this decrease is the increase of the ideality factor, so it could be said that the influence of the ideality factor on the solar cell efficiency is through the voltage. This is especially important because for non-ideal devices ideality factor n is greater than 1, indicating more complex temperature dependence of basic properties such as diffusion length or charge carrier lifetime.

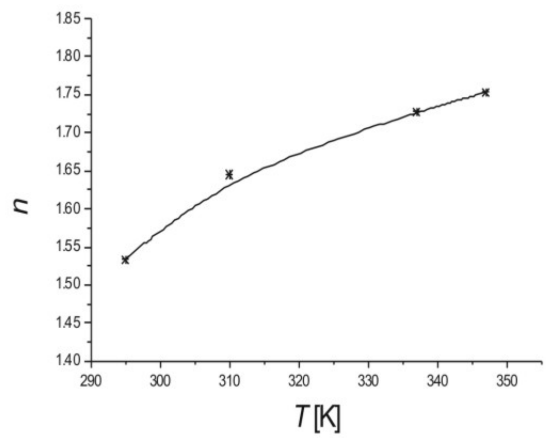

Figure 4: Temperature dependence of the ideality factor n.

Direct dependence of the ideality factor on the temperature for photo detector was shown in Fig. 4, where more or less linear increase of n could be seen. From the physical point of view, this behavior could be explained with the fact that, at the increased temperatures, imperfections of basic material are more pronounced. Namely, defects in the crystal lattice such as vacancies or interstices tend to accumulate when thermally stimulated, disturbing the periodicity of the potential field in the crystal. Such deviations could induce scattering of the charge carriers, and, consequently, a non-ideal behavior of the device, reflected in the values of n > 1. Besides, dislocations and impurities in the material with energy levels deep in the energy gap also tend to precipitate. Such localized energy states could act as traps or recombination centers for charge carriers, modulating output current and inducing current noise in photo detector devices (at low and medium voltages). Burst and 1/f noises are an example of the low frequency noises characterized by discrete current fluctuations, usually referred to as excess current. This excess current was observed in all samples at medium voltages, indicating the existence of the low frequency noises in the devices.

4. Conclusions

One of the major performance limitations of solar cells is the degradation of electrical and optical characteristics at increased temperatures. First part of the paper was oriented to the frequency dependent 1/f noise in contacts, since temperature increase induces higher level of noise. It was established that both physical and electrical properties of used silicides are influenced by the implantation doses. But the results of frequency noise measurements indicate that ion implantation could successfully be applied in order to achieve a more homogeneous silicidation and very good temperature stability, if carefully optimized dose (in our case $5x10^{15}$ ions/cm^2) was used. One of the most important characteristic of detectors such as solar cells is their energy resolution that primarily depends on noise, and that is why measurements of 1/f noise and improvement of silicides characteristics by lowering 1/f noise in them leads to the production of reliable and thermally stable contacts that could be used to improve solar cells.

On the other hand, from the I-V measurements obtained data have shown that though there is significant increase of solar cells current with an increase of temperature, other electrical characteristics rapidly degrade leading to the decrease of the efficiency. Owing to the strong correlation between burst noise and excess current, degradation of both electrical and optical output characteristics of the device could be monitored through the ideality factor. Obtaining the ideality factor from I-V measurements is quick, simple, non-invasive and effective way to evaluate possible degradation of output characteristics of solar cells and photodetectors in working conditions, and could be used to better understand solar cells. The observed increase of the ideality factor with the temperature indicates an increase of the current noise and detection threshold, and decrease of the resolution of the photo detector device. Although still in the working state, performances of such a detector (solar cell) at the increased temperatures are significantly deteriorated leading to the decrease of the precision of the output signal. For this reason monitoring of the device characteristics should be performed continuously, especially because solar cells are exposed to the severe working conditions such as increased temperature.

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