Increased Temperature and Radiation Damage Influence on Solar Cells Characteristics

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Possibilities for the application of solar systems based on photovoltaic conversion of solar energy are very wide, primarily because of their relatively low cost and very important fact that solar energy is most acceptable source of electrical energy from the environmental point of view. Solar cells, the basic elements for photovoltaic conversion of solar energy, are especially susceptible to high temperatures and radiation damage, primarily due to their large surface. Degradation of electrical and optical characteristics of the solar cells as 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, to some extent, on the temperature, investigations at temperatures higher than room temperature may reveal possible changes in output characteristics of the device. Also, the lifetime of the solar cell is restricted by the degree of radiation damage that the cell receives. This is an important factor that affects the performance of the solar cell in practical applications. Introduction of radiation-induced recombination centers reduces the minority carrier lifetime in the base layer of the p-n junction increasing series the resistance, and lead to an enormous increase of noise in solar cells. After very high doses of radiation series resistance of the base layer could be so high that most of the power generated by the device is dissipated by its own internal resistance. The aim of this paper is to investigate the influence of high temperature and radiation on output characteristics of solar cells as power generators of the future.

Keywords: *Solar cells, temperature effects, radiation damage, 1/f noise*

1. INTRODUCTION

Faced with an alarming increase of energy consumption on one side, and very limiting amounts of available conventional energy sources on the other, scientists have turned to the most promising, renewable energy sources. Photovoltaic (PV) conversion of solar energy is one of the most up-to-date semiconductor technologies that enables the application of PV systems for various purposes [1]. Telecommunications, electrification of small villages and remote areas such as national resorts and forests, as well as military communications are just a good example of the possibilities of PV system applications.

Development of the PV modules also leads to their utilization for lighting of indoor and out door spaces, signalization, refrigeration, irrigation and home water supply. As any other energy source, PV technology also has some limitations and disadvantages. In the first place, compared to some other sources, the efficiency of PV modules (i.e. solar cells) is relatively small. This means that photovoltaic conversion of solar energy is not suitable for high power consumers such as industrial applications. Also, seasonal character of solar irradiation availability could be considered as disadvantage, since energy storage presents some difficulties in both technological and economical aspects. But pollution free (sound) and environmentally acceptable technology makes PV systems one of the most promising renewable energy sources of electrical energy, especially in rural regions.

Based on a good experience, PV systems are nowadays used throughout the world for very different applications. Besides the fact that this is a good example of the application in isolated areas, it also presents the possibility of combining low cost of maintenance with pollution free and reliable technology. One other advantage of PV systems is that they could be mobile, together with the consumer.

Electricity provided by photovoltaics allows people living in rural areas to enjoy advantages of urban areas without leaving their traditional homes. Also, using photovoltaics as building materials has many advantages that are already applied in many developed countries of Western Europe. For example, solar panels cover the rooftops of a housing complex in Bremen, Germany [2], simplifying power production by eliminating many steps from extraction, processing, and transport fuel to a power station and sending that power over a great distance to electrify homes. Other

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advantages of photovoltaics include completely renewable nature, environmentally benign construction, absence of moving parts, modularity to meet any need from miliwatts to gigawatts, and one of the most important, readily available and permanent fuel source.

As the price of solar cells continue to drop, devices run by solar cells become more diverse, and the photovoltaic industry has experienced 20% annual growth rate over the last decade [2]. Nevertheless, photovoltaics are still not in the major league of power production, and for achieving that goal further reduction in their cost is necessary. The wider substitution of conventional energies by solar energy lies in the rate of developing solar cell technology. At present, most photovoltaic material is made from silicon grown as large cylindrical single crystals, and cutting cells only 300 or 400μm thick from such bulky materials demands excessive cutting, and half of the very expensive starting materials are wasted. That is the reason why many alternative manufacturing technologies are currently investigated. Also, at the beginning of the 21st century a novel approaches in investigations of materials for PV conversion were developed.

Namely, there is a new type of organic photovoltaic low cost solar cells based on the organic materials that uses the process of photosynthesis in plants that leads to photochemical processes. It is estimated that the production cost of these cells will be between 10% and 20% of the cost of solar cells produced in conventional way. Also, conducting and semiconducting polymers are considered as possible materials for solar cell production. New technologies in this field have given great contribution to the development of nanophotovoltaic cells with increased efficiency, such as quantum dots.

However, silicon is still the most used element for solar cell production, so efforts are directed to the improvement of physical properties of silicon structures.

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. Since one of the most important characteristics of detectors is their energy resolution that primarily depends on noise, lowering noise is important for obtaining good quality detectors.

Increased temperature influences all parts of a 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. It is known that low frequency noise (1/f and burst noise) is manifested as random fluctuation of the output current or voltage, leading to lowering of the efficiency of the device. Various experiments suggest [3,4] that the origin of this noise is fluctuation of the number of free charge carriers connected to the existence of the traps located in the vicinity or directly in the junction area, or fluctuation of the mobility of charge carriers. In both cases these fluctuations arise from the interactions of carriers with defects, surface states and impurities that are either introduced during manufacturing of the device, or as a consequence of the hostile working conditions (radiation, high temperature, humidity).

In order to function as a voltage generator with the best possible performances, beside p-n junction other thin films such as contact, antireflective, protective (oxide) thin films must be applied both on the front and on the back surface of solar cells. Because of the large surface to volume ration, surface effects are expected to be a major cause of 1/f noise, so good quality contacts are of great importance.

Silicides belong to a very promising group of materials with low resistivity and good temperature stability that are used for fabrication of reliable and reproducible contacts. Even so, surface effects such as surface recombination fluctuations in carrier mobility, concentration of surface states, etc., have great influence on frequency dependent noise also in silicides. It has been found [5, 6] that ion implantation of As+ ions in the formation of the silicides could improve electrical characteristics of silicides regarding their noise level.

Other most common source of noise that is connected to the hostile working conditions is radiation. For example, spent nuclear fuels also emit simultaneously, in addition to γ-rays, several neutrons, so the semiconducting device (e.g., solar cell) placed in the vicinity of these fuels sustains different kind of radiation damage both from γ-rays and from neutrons. The lifetime of the solar cell is restricted by the degree of radiation damage that the cell receives. This is an important factor that affects the performance of the solar cell in practical applications.

During the interaction with the material, radiation could deposit a large amount of energy that could induce various effects [7]. In semiconductors, for example, defects produced by radiation are connected to the localized energy states [8-10] that changes the concentration and mobility of the charge carriers. Namely, the main characteristic of semiconductors is a wide range of change in the concentration of charge carriers either due to existence of the impurities and defects or increased temperature. Direct recombination of the excess electrons and hole is a strictly forbidden process and they usually annihilate in the localized energy states in crystal. These are so called recombination centers, and imperfections with deep or multiple energy levels significantly stimulate the process of recombination.

Radiation induced defects fulfill these requirements and represent such recombination centers. The main effect of the radiation is an increase of the saturation current generated within or on the surface of the depletion region. The permanent damage of the device is caused by collisions of the incident radiation with the atoms in the crystalline lattice, which could be displaced from their positions, creating defect states [11,12]. Generation-recombination noise could be produced by fluctuations in the density of charge carriers caused by spontaneous fluctuations in the rate of generation, recombination and incidence of charge carriers. Also, the diffusion noise could increase in such conditions as a result of localized fluctuations both of the density of charge carriers, and the rate of diffusion. In both cases, these noises affect the level of the produced current.

Due to their wide range of application, solar cells are exposed to various kinds of radiation in working environment (cosmic rays, upper layers of the atmosphere, military and civil nuclear facilities etc.) [6]. That is the reason why very comprehensive investigations have been undertaken in order to develop semiconducting devices that could reliably operate in the conditions of the increased radiation [13-16]. From the technological point of view it is very important to establish changes in output characteristics of the device (current, voltage, and efficiency) induced by the radiation that affect their operation.

The main goal of this paper is to investigate the influence of working conditions, especially high temperature and radiation on the performance of the solar cells as photovoltaic generators.

2. EXPERIMENTAL PROCEDURE

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 1x1015 ions/cm2 to 1x1016 ions/cm2. 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: 21ºC 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.

For the effects of radiation, experimental measurements were performed on monocrystalline, nonencapsulated Si solar cell manufactured by Siemens. Current-voltage data were used for the characterization of the properties of solar cells. Standard measurement equipment was used to measure I-V curve under two different illumination levels (32 W/m2 and 58 W/m2). Reflective lamp was used as a solar simulator. From the obtained curves, all relevant parameters were obtained.

All samples were irradiated with gamma radiation. Before and after every step of the irradiation, current-voltage characteristics of the diodes were measured in highly controlled conditions at room temperature with combined measurement uncertainty less than 5%. One group of solar cells were irradiated with Co60 gamma source with different doses. Irradiation was performed through glass in controlled environment.

3. RESULTS AND DISCUSSION

Temperature dependence of 1/f noise in silicides

Though it is expected that thermal noise is dominant in the increased temperature conditions, other types of noises especially frequency dependent generation-recombination noise, burst noise and 1/f noise increase with the increase of the temperature. All of the effects that could lead to an increase of the 1/f noise (fluctuation of the number of free charge carriers and/or fluctuations in their mobility) 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. On the other hand, since all dynamic processes in semiconductor devices are temperature-dependent, investigations of temperature dependence of 1/f noise is very important for the performance of any device.

As it was expected, an increase in 1/f noise was also observed in this paper. Spectra of frequency dependent noise at lower (21ºC) and higher (50ºC) temperature are shown in Figures 1 and 2, respectively. Although proved to be stable and reliable as contacts, inherent presence of defects and impurities in the basic material of the silicides 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 in hostile conditions such as increased temperature. In such a case they become traps for electron-hole pairs, and thus decrease the number of collected charge carriers, producing noise in the device.

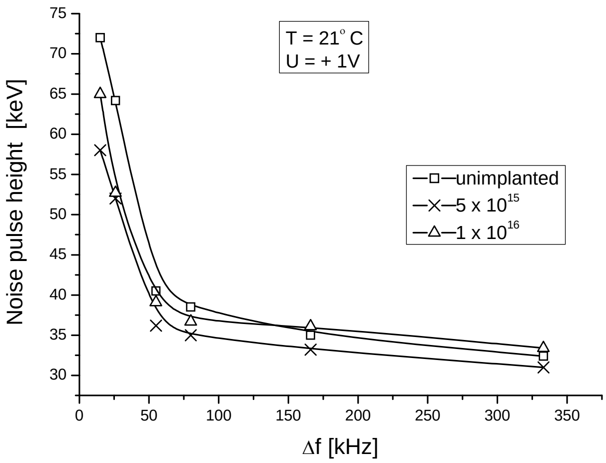

Fig. 1. Frequency noise level of two implanted and one unimplanted sample at 21ºC.

Increase of noise level with the increase of temperature is significant, especially when solar cells are concerned, due to specific working conditions (exposure to the solar radiation and inevitable increase of the temperature as a consequence - up to 40°C in the first 2-3 minutes of work).

Many output characteristics of solar cells, primarilly open circuit voltage (V_{oc}) and maximum power point voltage (V_m) decrease very rapidly when solar cells are exposed to the sun ($\partial V_{oc}/\partial T \approx 2.5$ mV/°C). This voltage decrease has great influence on the efficiency of solar cells.

Since temperature stability presents one of the most important characteristics of photovoltaic and any other semiconducting device, a large number of investigations were pointed in that direction.

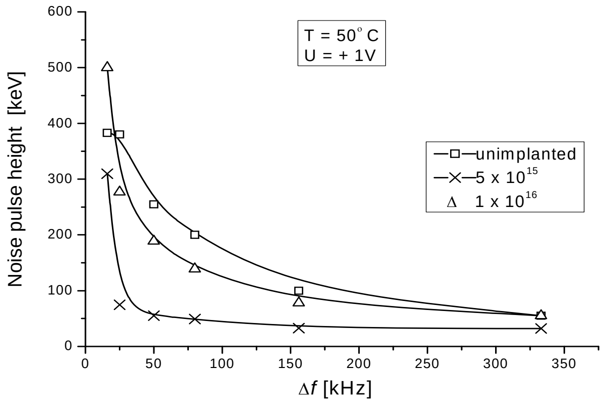

Fig. 2. Frequency noise level of two implanted and one unimplanted sample at 50ºC.

When silicides, as an important part of the front contact grid are concerned, many authors in their investigation discuss the problem related to the application of ion beam mixing of As+ ions for the formation of silicides [5,6]. Although introduction of As+ ions and their diffusion could change impurity concentration resulting in an increased noise level (especially for 1/f noise) in the structure, careful optimization of the implantation dose and subsequent thermal treatment such as annealing could result in the formation of stable contacts with a low noise level.

Every step of the silicides fabrication including the preparation of Si substartes, deposition of metal layer (Pd, Ti, and TiN, for example), As^+ ion implantation, and annealing must be taken into consideration in order to achieve the best possible result. Such a process was investigated in this paper for TiN/Ti/Si samples, and it was found that 1/f noise could be, to some extent, stabilized by controlled ion implantation, as could be seen in Fig. 1 and 2. Structural RBS analyses have shown that ion implantation did not induce redistribution of components for lower implantation doses, but for higher doses of implantation ($1x10^{16}$ ions/cm^2) a disordered structure was registered, and also higher level of noise.

This temperature dependent measurements indicate very important fact that ion implantation could provide temperature stability of silicides regarding 1/f noise. Namely, from Fig. 1 and 2 it could be seen that samples implanted with doses of $5x10^{15}$ions/cm^2 had lowest noise level and very good temperature stability, so it could be said that this dose of implantation induce a more homogeneous silicidation and the formation of Ti-Si phase with a lower concentration of crystal defects (after annealing). Also, previous results have shown [5] that the noise level was lowest for the samples implanted after annealing. This suggests that thermal treatment induce relaxation of crystal lattice and improvement of the crystal structure of the silicides. This could lead to an improvement of electrical characteristics of silicides and devices based on silicides as contacts (for example, solar cells).

Radiation effects

When radiation effects are concerned, during interaction of γ radiarion with the device, and depending on the radiation energy, primarilly three effects could occur: photoelectric effect, Compton effect, and electron-hole creation. In all of these processe, absorbed photon energy causes ionization and excitation of the created electrons, with the electron-hole creation. These effects lead to the generation of parasitic charge (noise) collected in the depletion region.

Also, ionization effects could produce recombination centers in the energy gap. In silicon, all of these effects could be permanent or quasi-permanent, and in solar cells produce the decrease in all output characteristics. From the standpoint of the energy production, two main output charateristisc of solar cells are maximum power point P_m, and efficiency η. As could be seen from Fig.3 (the dependence of maximum power (P_m) on doses for two illumination levels), gamma radiation produces an inevitable decrease in the P_m.

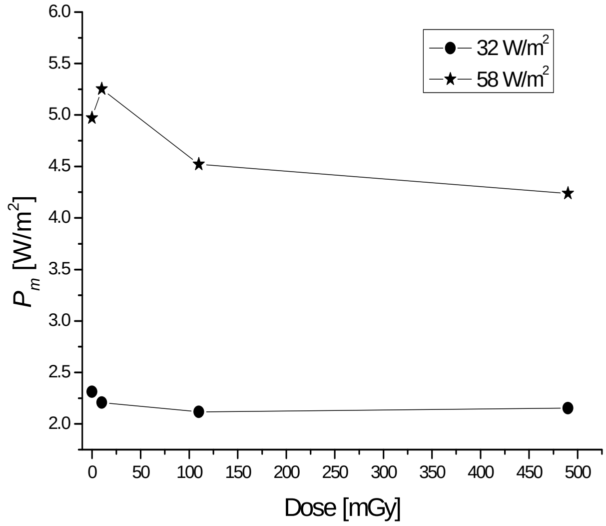

Fig. 3. Dependence of the maximum power on doses (gamma irradiation).

Besides expected decrease of the output characteristics with an increase of doses, for higher illumination level a slight increase of Pm was observed. This increase is very significant from the standpoint of solar cell as a power generator, because it indicates possible beneficent influence of low doses of irradiation.

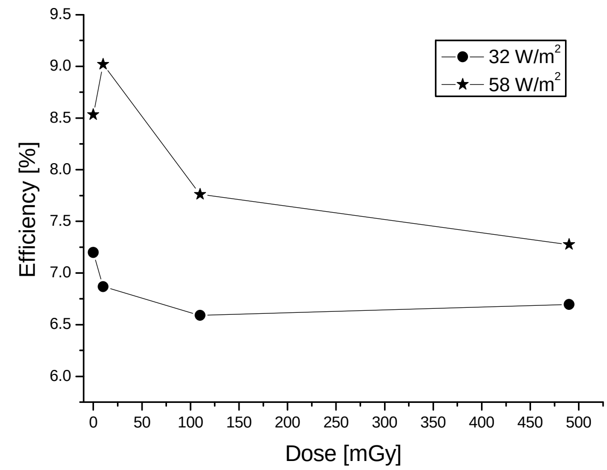

Fig. 4. Dependence of the efficiency on doses (gamma irradiation).

It could be explained by the fact that during the fabrication processes, structural defects and impurities that were unavoidably made, produce tension in the crystal lattice. Interaction of irradiation with such a material could act similarly to annealing, relaxing lattice structure and decreasing series resistance, ultimately leading to the increase of the efficiency (Fig.4).

4. CONCLUSION

Single element optical detectors such as solar cells and photodiodes are the final component needed for communications or optical information processing systems. Since one of the major performance limitations of solar cells is the degradation of their electrical and optical characteristics in the increased temperature conditions and in radiation environment, measurements and lowering of noise level are very important for improvement of solar cells characteristics.The First part of the paper was oriented to the frequency dependent 1/f noise in contacts, since temperature increase induces a 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 was used.

Effects of gamma irradiation on solar cells have shown, that, though commonly referred to as a source of noise in semiconducting devices, that radiation induced effects could have in some cases positive effect on the main electrical characteristics (Pm, η). Nevertheless, permanent monitoring of the relevant solar cell characteristics when working in hostile conditions is very important, since performance failure could have negative impact both on the financial and environmental aspects of the device application.

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УТИЦАЈ ПОВИШЕНЕ ТЕМПЕРАТУРЕ И РАДИЈАЦИОНИХ ОШТЕЋЕЊА НА КАРАКТЕРИСТИКЕ СОЛАРНИХ ЋЕЛИЈА

Александра Васић-Миловановић

Могућности примене соларних система базираних на фотонапонској конверзији соларне енергије су веома широке, првенствено због њене релативно

ниске цене, као и веома важне чињенице да соларна енергија представља најприхварљивији извор електричне енергије са становишта заштите човекове околине. Соларне ћелије, основни елемент конверзије соларне енергије су посебно осетљиве на повишену температуру и радијациона оштећења, првенствено због њихове велике површине. Деградација електричних и оптичких карактеристика соларних ћелија као фото детектора у условима повишене температуре је један од најважнијих ограничавајућих фактора за њихову примену. С обзиром на то да већина електричних процеса у полупроводничким уређајима, у извесној мери зависи од температуре, истраживања на температурама вишим од собне могу да открију могуће промене излазних карактеристика уређаја. Такође, радни век соларне ћелије је ограничен степеном радијационих оштећења. То је звачајан фактор који утиче на рад соларне ћелије у практичној примени. Увођење радијацијом индукованих рекомбинационих центара смањује се време живота носилаца у базном слоју p-n споја повећавајући редну отпорност, што доводи до изразитог пораста шума код соларних ћелија. После примљених веома великих доза зрачења, редна отпорност базног слоја може бити толико велика да већи део снаге коју уређај произведе може да се дисипира његовом сопственом унутрашњом отпорношћу. Циљ овог рада је да проучи утицај повишене температуре и зрачења на излазне карактеристике соларних ћелија као енергетског извора будућности.