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Study of the Relaxation of the Excess Current in Silicon Schottky Diodes

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Abstract—This study is devoted to investigation of the relaxation of excess current in silicon α-NiTi–*n*-Si Schottky diodes subjected to either γ-ray radiation or local disturbance of the interface structure using a diamond indenter. A decrease in the excess diode current is attained using both thermal annealing and ultrasound irradiation. Simultaneously, the parameters of solar cells manufactured from the above-mentioned Schottky diodes subjected to irradiation with γ-ray photons and to single or double irradiation with ultrasound are studied. It is shown that, after the effect of the diamond indenter, the excess current decreases as a result of thermal annealing; however, a decrease in the excess current to the initial value is not attained. The photoelectric parameters of the studied solar cells before irradiation and after irradiation with γ-ray photons and after single or double irradiation with ultrasound show that ultrasonic treatment is more efficient than thermal annealing.

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1. INTRODUCTION

An increase in the reliability and improvement of the quality of electronic devices, including those based on a Schottky barrier, are still considered as an urgent need in modern semiconductor technology [1–3]. As is known, the irradiation of semiconductor devices with charged high-energy particles results in the accumulation of radiation defects in the volume of a semiconductor; this brings about substantial deterioration of the electrical and photoelectric characteristics of devices [4–6]. Traditionally, heat treatment is used to recover the perturbed properties of irradiated materials; the use of this treatment leads to some negative consequences [7–8]. Therefore, as an alternative, it is often that attention is paid to athermal ways of treatment, one of which is ultrasound treatment (UST). Ultrasound treatment is an efficient method for increasing the internal energy of solids. Depending on the absorption coefficient and the intensity of ultrasound, various structural variations are possible; the latter affect the photoelectric and electrical properties of materials and also the process of plastic deformation [6, 8, 9].

Under the effect of some external factors at low forward voltages in Schottky diodes (SDs) and solar cells (SCs), one may observe excess currents, which is reflected in their current–voltage (*I*–*V*) characteristics and can represent the relaxation of an excess current in a SD or a SC. It is assumed that the disturbed *I*–*V* characteristics contain important information necessary for establishing the true nature of processes occurring at interfaces and the processes of charge transport in the metal–semiconductor contact (MSC) [5, 6, 9].

In connection with this, it is of interest to study the relaxation of excess current in silicon α-NiTi–*n*-Si SDs subjected to local disturbance of the interface structure with the use of a diamond indenter in relation to the annealing time at different annealing temperatures; at the same time, we also studied the SC parameters before irradiation, after irradiation with γ-ray photons, and after single or double ultrasound treatment.

2. EXPERIMENTAL

In order to fabricate the SD and SC devices made by SD technology with a transparent window, a silicon wafer with *n*-type conductivity, with (111) orientation, and with a resistivity of 0.7 Ω cm was used. The matrix included 14 diodes, the areas of which varied in the range from 100 to 1400 μm^2. In the case under consideration, the area of the SD contact was 500 μm^2, the thickness of the silicon wafers was 280 μm, and the thickness of the NiTi film was $d_{\mathrm{NiTi}} = 0.5$ μm. The film is illuminated perpendicular to the SC surface. To deposit the film of the α-NiTi metal alloy, a commercial ORATORIYA-9 setup was used. The metal α-NiTi alloy was deposited by the method of electron-beam sputtering from two sources. The Ni–Ti alloy was chosen from the considerations that both components are widely used in microelectronics, while the alloy itself is easily produced. The SCs were irradiated with ^{60}Co γ-ray photons with a dose of ~10^6 rad at room temperature. Then these samples were consecu-

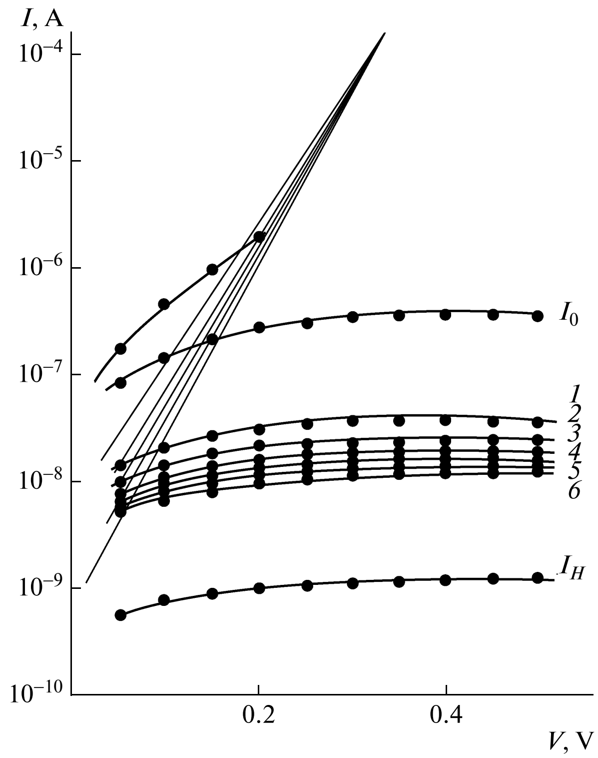

Fig. 1. *I–V* characteristic illustrating the degradation properties of an α-NiTi–*n*-Si SD in the I_N (normal) and I_0 (artificially degraded and annealed at 400°C) states; annealing was performed for t = (*1*) 17, (*2*) 65, (*3*) 148, (*4*) 260, (*5*) 410, and (*6*) 580 s. The measurements were performed at a constant reverse current at V_{rev} = 0.2 V.

tively, in two stages, subjected to UST; a longitudinal wave was introduced to the rear side of the sample, perpendicular to its working surface. In the first stage, UST-1 (the frequency of ultrasound (us) $f_{us} \approx 95$ MHz, the intensity $W_{us} \approx 0.55$ W/cm^2, and the duration $t \approx$ 120 min); in the second stage, UST-2, ($f_{us} \approx 30$ MHz, $W_{us} \approx 15$ W/cm^2, and $t \approx 200$ min). After each stage of UST, the current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics of the SCs were measured in a wide temperature range (100–350 K). The values of the lifetime of the minority charge carriers τ_n and of the effective concentration of ionized centers N_{eff} were determined from the *C–V* measurements [10, 11].

A study of the relaxation of excess current in the *I–V* characteristic of a SD is based on the fact that this relaxation is rarely observed under normal conditions; therefore, in order to study in detail the corresponding issues, the *I–V* characteristic of a SD degraded intentionally by local disturbance of the interface was studied [7, 9]. Using a PMT-3 microhardness meter, an inhomogeneity at the interface of the metal–semiconductor contact was artificially formed. The diamond needle of the adapter is a regular quadrangular pyramid with an angle of 136° between opposite faces. The area of the disturbed regions was varied by changing the value of the load *F*(100 g) and the number of disturbances *N*(1) (Fig. 1). After disturbance of the interface, the value of the current flowing through the diode is equal to the sum of currents flowing through the disturbed and undisturbed regions. As the mechanical pressure *F* and the number of disturbed regions *N* are increased, the value of the ratio of currents increases linearly [9].

Thermal annealing of the diodes was performed at temperatures of 100–400°C for the same duration of annealing t = 20 min. The relaxation of excess current in α-NiTi–*n*-Si SD was determined as a function of the annealing duration *t* (17–600 s) at different annealing temperatures (200, 300, and 400°C).

3. RESULTS AND DISCUSSION

For quantitative characterization of the relaxation of excess current as a result of thermal annealing with the annealing duration taken into account, the following formula was used:

$$\alpha_t = \frac{I_t - I_n}{I_0 - I_n};$$

here, I_n is the current of a normal (undamaged) Schottky diode, I_0 is the current through the diode immediately after the effect of the indenter ($t = 0$), and I_t is the current through the disturbed diode annealed for *t* seconds, and α_t is the characteristic of the relaxation of excess current under the effect of thermal annealing in the time *t*.

Figure 1 shows the *I–V* characteristics in the case of the relaxation of excess current in the α-NiTi–*n*-Si SDs subjected to local disruption of the interface structure with the use of a diamond indenter (under a load of *F*(100 g), the number of disturbances $N = 1$) before and after annealing at 400°C for a time of (*1*) 17, (*2*) 65, (*3*) 148, (*4*) 260, (*5*) 410, and (*6*) 580 s. The excess current originating in a SD passes through the mechanically disrupted regions of the contact near the interface [9]. The study of the relaxation of excess current in α-NiTi–*n*-Si SD was carried out by measuring the *I–V* characteristics both in the forward and reverse directions. The reverse portions of the *I–V* characteristics were used in calculation of the parameters.

Figure 2 shows the dependence of α_t on the annealing time at various annealing temperatures and at constant reverse current corresponding to V_{rev} = 0.2 V. As follows from Fig. 2, α_t depends heavily on both T_{ann} and on *t*. As the annealing parameters are altered, the value of α_t varied in the range $0 \le \alpha_t \le 1$. It follows from the obtained results that, first, the main stage in the process of annealing occurs in short initial annealing times, and, second, the main stage of the annealing process "heals" (the characteristics of relaxation, i.e., of a decrease in the excess current under the effect of annealing) the disrupted diodes; the *I–V* characteristics of the α-NiTi–*n*-Si disrupted SDs are very sensitive to the duration of annealing. With an increase in time (even at room temperature), the level of the excess current decreases, i.e., the damage induced by the mechanical effect is “healed”. The process of a decrease in the excess current speeds up if the annealing temperature is higher and the annealing time is longer.

The parameters of a SC before and after corresponding treatments are listed in Tables 1 and 2. It is shown that irradiation with γ-ray photons adversely affects both the reverse and forward I–V characteristics and deteriorate them compared with the initial characteristics (the reverse current I_{rev} is increased) [5, 6, 8].

The effect of irradiation with γ-ray photons and of UST directly on the photoelectric and electrical characteristics of the SCs under study can be deduced from Tables 1 and 2; the parameters of both the sample and the corresponding SC are given. The photocurrent is determined by the following formula [10]:

$$I_{ph} = qSN_{ph}Q;$$

here, q is the elementary charge, SN_{ph} is the total number of photogenerated electron–hole pairs at the area S, and Q is the collection coefficient for charge carriers. Since the value of SN_{ph} remains practically constant under conditions of the experiment under consideration, a decrease in the SC photocurrent as a result of irradiation with γ-ray photons is evidently caused by a decrease in Q. In the case where the diffusion length of minority charge carriers in the base $L_n \ll d_p$, the quantity Q is defined by the formula [10, 11]

$$Q = \frac{\alpha L_n}{\alpha L_n + 1}, \tag{1}$$

where α is the absorption coefficient of light.

It is known that $L_n = \sqrt{D_n \tau_n}$, where D_n is the diffusion coefficient and τ_n is the lifetime of minority charge carriers in the base.

Taking into account (1), the following expression is obtained for the photocurrent:

$$I_{ph} = qSN_c \frac{\delta\sqrt{D_n\tau_n}}{\delta\sqrt{D_n\tau_n} + 1}.$$

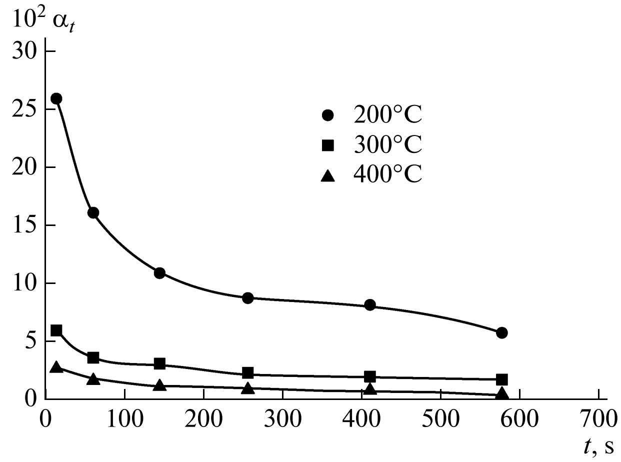

Fig. 2. Dependence of α_t on the annealing duration at different annealing temperatures.

The open-circuit voltage U_{oc} is determined as

$$U_{oc} = \frac{AkT}{q}\ln\left(\frac{I_{sc}}{I_{0\,rev}}\right), \tag{2}$$

where k is the Boltzmann constant, T is temperature, I_{sc} is the short-circuit current, U_{oc} is the open-circuit voltage, A is a dimensionless coefficient, P_{max} is the maximal output power, and ξ is the filling factor. The electrical parameters also include τ_n, the lifetime of minority charge carriers; L_n, the diffusion length of minority charge carriers; $I_{0\,rev}$, the reverse saturation current; N_{eff}, effective concentration of ionized centers; and E_a, the activation energy.

Irradiation with γ-ray photons results in a decrease in both the short-circuit current I_{sc} and open-circuit voltage U_{oc}; as a consequence, the maximal output power decreases. Subsequent ultrasound treatments (UST-1 and, especially, UST-2) restore the SC parameters, so that the initial values are met. Irradiation with ^{60}Co γ-ray photons with an energy on the order of ~1.35 MeV is equivalent to the internal irradiation of a SC with fast electrons, which appear as a result of Compton scattering and photoabsorption, and results mainly in the formation of point defects. The studies (UST-1 and, especially, UST-2) of silicon SCs performed in two stages were indicative of a

Table 1. Photoelectric parameters of α-NiTi/Si in a SC sample before and after irradiation with γ-ray photons and also after UST at $P_l = 100$ W/cm^2 and $T = 25$°C

The state of the sample	Parameters				
	A	U_{oc}, V	I_c, mA	P, mW	ξ
Before irradiation	2.57	0.526	28.6	10.81	0.7186
After γ irradiation	2.86	0.482	23.14	7.99	0.7161
After UST-1	2.77	0.505	24.62	8.92	0.7172
After UST-2	2.66	0.518	27.7	10.31	0.7189

Table 2. Electrical parameters of an α-NiTi/Si sample of SC before and after irradiation with γ-ray photons and also after UST at $P_l = 100$ W/cm^2 and $T = 25$°C

State of the sample	Parameters				
	N_{eff}, cm^{-3}	E_a	I_0, μA	L_n, μm	τ_n, μs
Before irradiation	2.17×10^{16}	0.71	88.21	51.0	0.781
After γ irradiation	3.14×10^{16}	0.55	287.2	44.9	0.602
After UST-1	2.92×10^{16}	0.61	276.1	48.5	0.703
After UST-2	2.48×10^{16}	0.69	135.3	49.6	0.732

decrease in N_{eff} (Table 2), which is a manifestation of the athermal annealing of radiation centers. As is known, annealing of radiation centers can correspond to several mechanisms: the migration of defects to sinks [4–6, 9, 11], formation of a more complex defect, dissociation of the complex, and so on.

Thus, the UST is an effective method for increasing the internal energy of solids. In contrast to thermal energy absorbed uniformly in the entire volume of a semiconductor, attenuation of the UST waves occurs mainly at crystal-lattice defects and contributes to their redistribution and the equilibrium state [5, 7].

4. CONCLUSIONS

It is found that relaxation of the irradiation-induced degradation can result from thermal and ultrasound treatments of α-NiTi—n-Si Schottky diode and is related to a variation in the parameters of annealing; in this study, the degree of relaxation varied in the range $0 \le \alpha_t \le 1$, with the radiation-damaged diodes "healed" during the course of the main stage of the annealing process. Simultaneously, experimental results indicating that it is possible to recover and control the parameters of silicon solar cells (SCs) using ultrasound treatment (UST) are considered. The recovery of the initial electrical and photoelectric SC properties (disrupted by irradiation with γ-ray photons) with the use of UST is related to the regrouping and athermal annealing of radiation defects formed by the γ-ray photons.

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