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A study of electrical properties of dislocation engineered Si processed by ultrasound

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A B S T R A C T

This work presents experimental study of electrical properties of dislocation engineered Si *p–n* junction before and after the influence of ultrasound waves. We have studied current–voltage characteristics in the dark and upon illumination for forward and reverse biases before and after ultrasound processing. By fitting the theoretically established current–voltage dependence to the experimentally measured ones, the diode ideality factor and saturation current have been estimated. It is found that current transport through the dislocation-engineered Si *p–n* junction can be controlled by generation-recombination or tunneling recombination mechanisms. Ultrasound is found to modulate electrical properties of the dislocation engineered Si.

1. Introduction

Since the discovery [1–3] of luminescent feature, study of dislocation engineered (DE) Si is one of the interesting scientific topics. Distinct from bulk Si, luminescence intensity of DE Si is found to increase with increasing the temperature from low to $T = 300\,K$. Here the strain field around dislocations plays an important role. On the one hand it modulates band structure, provides carrier confinement, and suppresses diffusion of charge carriers to the surface, thus enhancing radiative recombination and luminescence intensity of the DE Si. On the other hand, the strain field can be the source for aggregation of defects and impurities, which can enhance non-radiative recombination of charge carriers and thus partially suppress radiative recombination and luminescence. To solve the problem, passivation by hydrogen [4] and annealing at high temperatures $>200\,^{\circ}C$ can be used. However, the high temperature annealing can result in quenching the luminescence of DE Si [5]. Thus search of the alternative ways of annealing at moderate temperatures without destroying the luminescence properties of DE Si is an important problem. Ultrasound treatment (UST) could be the alternative way [6–8]. According to scientific literature, UST has successfully been used so far for metal cluster engineering in ion implanted silicon dioxide [9], defect engineering in Si *p–n* junctions [10], silicon based impact ionization avalanche transit-time (IMPATT) diodes [11,12], power Schottky diodes and Zener diodes [13,14], extension of spectral sensitivity of the AlGaAs/GaAs solar cells toward short-wave lengths [15], modification of radiation-induced defects in Si [16], etc. The aim of this paper is to study the effect of ultrasound on electrical current transport in dislocation engineered Si *p–n* junction.

2. Experimental details

The samples studied in the paper are fabricated by boron implantation into Czochralski (CZ) P-doped *n*-type Si ($2–7\,\Omega\,cm$) with a contact area of $1.76\,mm^2$ and a width of 1.00 mm. The boron-implantation induced dislocation loops located at ~300–700 nm from the Si surface have been detected by TEM analysis [17–19]. Total number of loops is $\sim 3–6 \times 10^9\,cm^2$. More details on preparation of samples can be found somewhere else (see, e.g., Refs. [17–20]). Three groups of samples denoted by A1–A4, B1–B4, and C1–C4 have been studied (Table 1). S impurities have been implanted into the A1–A4 samples of dose $10^{14}\,cm^{-2}$ with annealing temperature of $1000\,^{\circ}C$ and B1–B4 samples of dose $10^{13}\,cm^{-2}$ with rapid thermal annealing at $1100\,^{\circ}C$. The C1–C4 samples do not contain S impurities.

Sulphur related luminescence of Si has been studied before (see, e.g., Refs. [21–23]), however, no room temperature luminescence has been found. After the dislocation engineered Si light-emitting diode was first fabricated [3] effect of additional doping with sulphur impurities was also studied [20]. Below we study the effect of UST on the electrical properties of the sulphur-doped dislocation engineered Si. UST of the samples has been performed from the contact side by ceramic piezoconvertor. Frequency of the

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Table 1
Sulphur implantation dose D (cm^{-2}), annealing temperature T (°C) to activate the sulphur atoms, UST power P and time τ_{UST}, ideality coefficient β and saturation current J_0 before and after UST.

Samples	D (cm^{-2})	T (°C)	P (W/cm^2)	τ_{UST} (min)	β		J_0 (μA/cm^2)	
					Before UST	After UST	Before UST	After UST
B1	10^{13}	1100	1.0	15	2.4	3.1	3.5	15.2
B3			0.5	30	2.3	2.3	3.3	3.6
B4			0.5	15	3.4	3.8	24.2	47.3
A1	10^{14}	1000	1.0	15	2.9	3.0	10.3	18.0
A2			1.0	30	2.8	2.8	8.0	9.5
A3			0.5	30	3.5	3.3	19.8	16.9
A4			0.5	15	2.3	2.5	2.6	3.5
C1	0	0	1.0	15	2.0	2.1	0.6	0.7
C2			1.0	30	1.8	2.0	0.4	0.5
C3			0.5	15	2.5	2.4	3.3	2.8
C4			0.5	30	1.9	2.0	0.9	0.5

UST was 2.4 MHz. The UST has been done in alcohol. Samples have been treated by ultrasound of powers 0.5 and 1.0 W/cm^2 within 15 and 30 min (Table 1).

Dependence of electrical current density J on the applied voltage V has been studied for forward and reverse biases. The results have been fitted with the formula

$$J = J_0\left[\exp\left(\frac{qV}{\beta kT}\right) - 1\right]. \quad (1)$$

From the fitting the diode ideality factor β and saturation current

$$J_0 = q\frac{n_i^2}{N_d}\sqrt{\frac{D_p}{\tau_p}} \quad (2)$$

has been determined. Here T is the temperature, k the Boltzmann constant, q the electron charge, n_i the intrinsic carrier concentration, N_d the concentration of shallow donors, and D_p and τ_p are the hole diffusion coefficient and lifetime, respectively. The measurements have been performed at room temperature.

3. Results and discussions

For efficient transfer of energy of the ultrasound to samples the treatment is commonly done in technical alcohol or distilled water, which are not well reactive for the samples considered. Ultrasound treatment of the reference samples in both the media showed similar results, which indicates that modulation of properties of the samples can be ascribed to ultrasound rather than surface treatment by alcohol. Based on this result UST of the samples has been performed in alcohol.

Since the samples are of DE Si, one can expect that current transport is controlled by carrier recombination. To check the validity of the statement and to establish current transport mechanism, current–voltage dependence has been studied in the dark and upon illumination for forward and reverse biases before and after UST. Diodic characteristic has been observed for all the samples considered. The results for the sample B1 have been presented in Fig. 1(a) and (b) for forward and reverse biases, respectively. Fig. 1(a) has been plotted in semilogarithmic scale. It is seen that in the voltage range of ~0.1–0.4 the J–V curve is almost linear, which means that the J–V dependence is exponential. So, for the voltage range the J–V dependence can be described by Eq. (1). Fitting of the Eq. (1) to the experimental results presented in Fig. 1(a) has been performed. Analysis shows that the J–V dependencies in forward bias are well described by Eq. (1). Upon treating by ultrasound the electrical current J increases. It indicates that UST leads to partial inhibition of

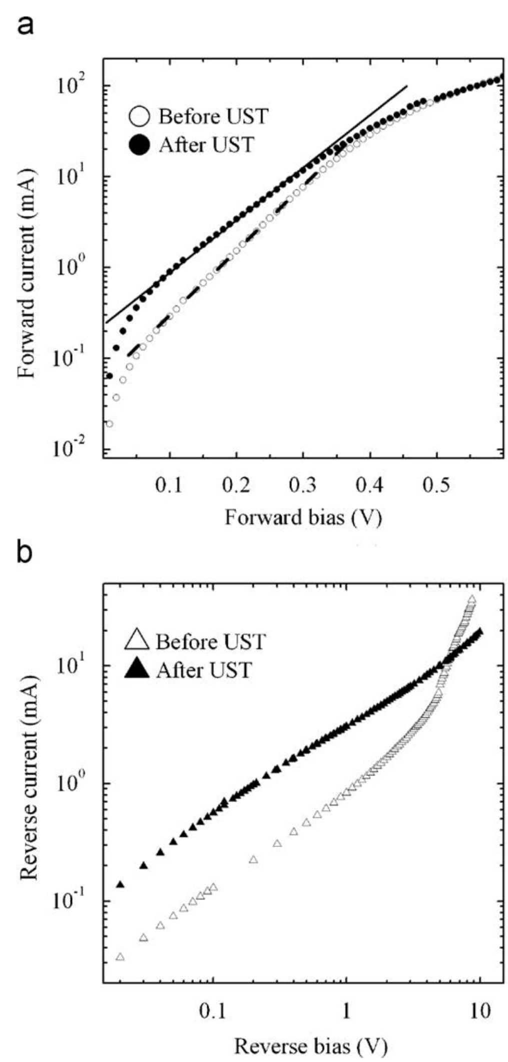

Fig. 1. Experimentally measured dark current–voltage characteristics for sample B1 for (a) forward and (b) reverse biases before (○, △) and after (●, ▲) UST. (a) The solid and dashed straight lines indicate that the J–V dependence can be described by linear relationship, i.e. by the Eq. (1) and (b) for convenience of analysis the values of J and V have been multiplied to (−1) and the figure has been plotted in the first quadrant.

generation-recombination processes by reducing the concentration of recombination-active deep traps decorating the dislocations. This result is consistent with lifetime measurements

[27] by open-circuit voltage decay method, which demonstrated an increase of carrier lifetime.

By fitting Eq. (1) to the measured data saturation current J_0 and ideality factor β have been determined (Table 1). Analysis of Table 1 shows that ideality factor is much larger than 2.00 for the samples A1, A2, A3, and B4. It indicates that current transport is basically controlled by tunnelling-recombination mechanism. However, magnitude of β for most of the samples is around 2, which shows that in those samples current transport is controlled by generation-recombination processes. Saturation current J_0 is very large for all the samples considered. The reason can be related to the presence of deep level defects located around the dislocations.

Upon annealing by ultrasound, defect spectra in all of the samples have been considerably modulated. First of all this should leave to modulation of J_0 and β. In samples A3, C3, and C4, magnitudes of both J_0 and β have been reduced, which demonstrates UST-induced annealing of the deep traps. However, in rest of the samples J_0 and β has been increased, which demonstrates UST-induced formation of the recombination active centers.

For the convenience of analysis the values of J and V in Fig. 1(b) have been multiplied to minus one and the figure has been plotted in the first quadrant. Analysis of current–voltage characteristics for reverse bias (Fig. 1(b)) showed that it can be described by 6th order polynomial

$$J(V) \approx J(0) + a_1 \times V + a_2 \times V^2 + a_3 \times V^3 + a_4 \times V^4 + a_5 \times V^5 + a_6 \times V^6, \tag{3}$$

Here a_1–a_6 are coefficients of the polynomial determined from fitting of Eq. (3) to the experimentally measured data. This result shows that the defects responsible for carrier recombination form a continuous energy band in the band gap. One can expect this result because the samples are light-emitting diodes with dislocation loops. Generation-recombination processes are controlled by dislocations and as is well known [24] the dislocation related bands in Si are continuous.

Analysis of Fig. 1(b) shows that the J–V dependencies for reverse bias before and after UST differ from each other. The reason can be related to UST-stimulated modulation of recombination activity of the dislocations. As noted in Ref. [25], strain field around dislocations can modulate band structure of Si. So, on the one hand the experimental observation can be the result of the UST-induced transformation of the dislocations, which has lead to change of their recombination properties. On the other hand, the UST modulation of defects can lead to variation of the concentration and lifetime of the carrier confined in the dislocation loops, which can be released at larger reverse voltages and contribute to the reverse current. So, at present the safest conclusion is that the difference on the reverse J–V dependencies before and after UST can be related to UST-induced modulation of recombination activity of dislocations.

Current–voltage dependence has been studied not only in the dark, but also upon illumination. From the study it is found that the samples possess photovoltaic (PV) feature. In all the samples photovoltage and photocurrent have been generated. Fig. 2(a) and (b) display the J–V curves corresponding to the sample C2 for different illumination intensities (a) before and (b) after UST. As expected, the PV performance of the device structure is too small, because the main aim of incorporation of the dislocation loops is to provide the confinement of non-equilibrium charge carriers and to enhance the rate of their radiative recombination rate thus enhancing the intensity of light emission. UST further reduced the PV performance. Similar result has been obtained for the sample C2. For some of the samples the feature has been enhanced.

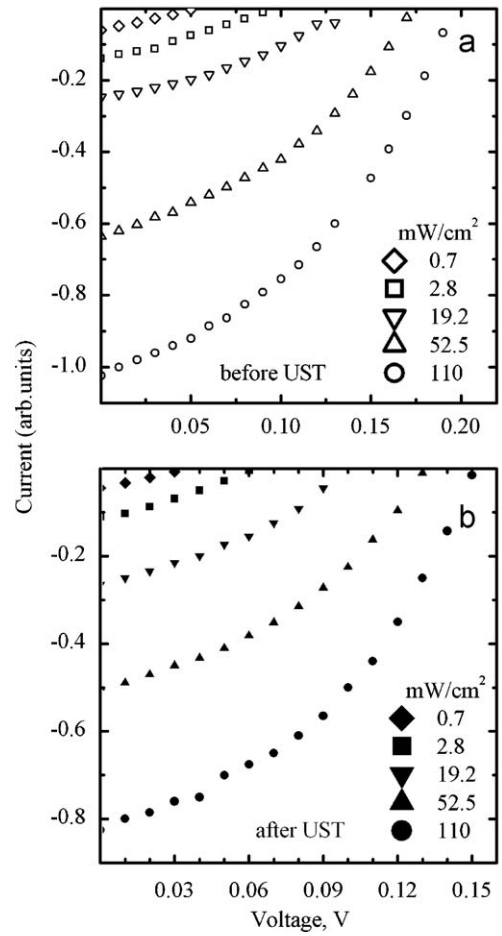

Fig. 2. Current–voltage characteristics for sample C2 (a) before and (b) after UST for different illumination intensities.

Such device structures are expected to be sensitive to variations of the illumination intensity. This feature is available in our samples as well. Fig. 3 shows the dependence of short-circuit current J_{sc} (Fig. 3(a)) and open-circuit voltage V_{oc} (Fig. 3(b)) on illumination intensity Φ. It is seen that at smaller Φ both of the parameters characterizing PV feature of the samples increase sharply with increasing Φ thus demonstrating high sensitivity of the samples to illumination. At larger values of Φ both J_{sc} and V_{oc} slightly increase.

As it is well known, J_{sc} is related to carrier lifetime through the relation [26]

$$J_{sc} = q\Phi \cosh(W/L_p), \tag{4}$$

where $L_p = \sqrt{D_p \tau_p}$ is the diffusion length of free holes. W is thickness of the base layer, and Φ is the incident photon flux creating free carriers. Based on Eq. (4) one can suggest that the UST-induced enhancement of J_{sc} (Fig. 3(a)) can be caused by that of carrier lifetime. This result is consistent with that of Ref. [27], which reported about the UST-induced increase of carrier lifetime for the sample A1 (Fig. 3) determined from analysis of the open-circuit voltage V_{oc} decay transient.

Since the equilibrium and non-equilibrium concentrations of free holes p_0 and p are related to each other through the relation

$$p = p_0 \exp\left(\frac{qV_{oc}}{\beta kT}\right) \tag{5}$$

the UST-induced enhancement of V_{oc} (Fig. 2(b)) indicates that free carrier concentration has been increased as well. The relation p/p_0 has been estimated using the measured values of V_{oc} before and

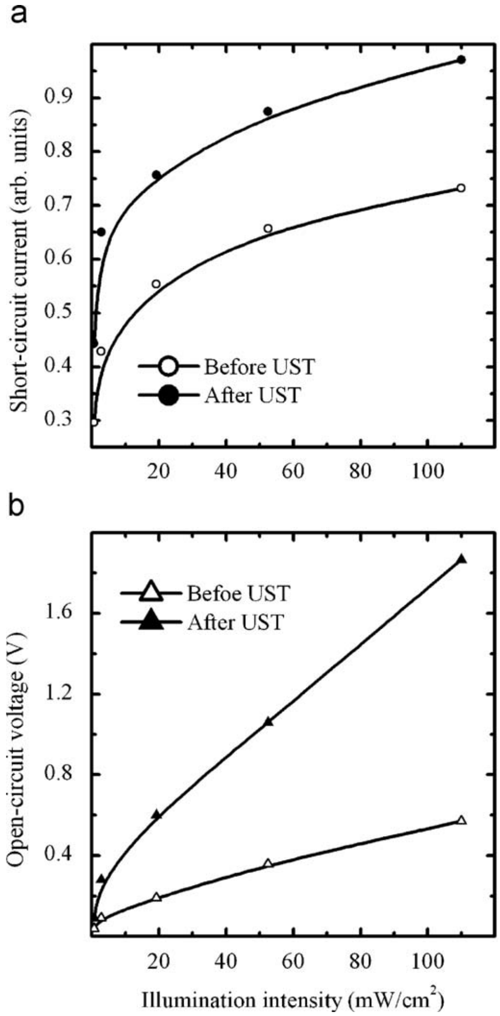

Fig. 3. Dependence of (a) photocurrent and (b) photovoltage on illumination intensity for the sample A1 before and after UST.

after UST. It is found that after UST p/p_0 has been increased $\sim 10^2$ times.

4. Conclusion

Current–voltage characteristics have been studied for the dislocation engineered Si p–n junction for forward and reverse biases in the dark and upon illumination before and after ultrasound treatment. Saturation current, ideality factor have been estimated for each of the cases. It is found that the diode ideality factor is in the range 1.8–3.5 before and 2.0–3.8 after ultrasound treatment. This result means that generation-recombination and tunnelling recombination mechanisms of current transport can take place. By analysis of the dark and light current–voltage dependencies before and after ultrasound treatment we show that by ultrasound processing it is possible to modulate the diode ideality factor for the samples except sample C3 by varying the ultrasound power, frequency, and duration. Ultrasound can cause transformation of structural defects, which plays important role in transport properties of the dislocation engineered Si.

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