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ФИЗИКА КОНДЕНСИРОВАННОГО СОСТОЯНИЯ И ПРОБЛЕМЫ МАТЕРИАЛОВЕДЕНИЯ

A STUDY OF ELECTRICAL PROPERTIES OF DISLOCATION ENGINEERED Si PROCESSED BY ULTRASOUND

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Abstract

This work presents experimental study of electrical properties of dislocation engineered Si *p-n* junction before and after 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.

Keywords: dislocation engineering, current transport, ultrasound treatment

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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 °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 luminescence properties of DE Si is an important prolem. 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], extension of spectral sensitivity of the AlGaAs/GaAs solar cells toward short-wave lengths [11], modification of radiation-induced defects in Si [12], etc. The aim of this paper is to study 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) *n*-type Si. Presence of the boron-implantation induced dislocation loops have been detected by TEM analysis [14-16]. More details on preparation of samples can be found somewhere else (see, e.g., Refs. [13-16]). Three groups of samples denoted by A1-A4, B1-B4, and C1-C4 have been studied (Table I). S impurities have been implanted into the A1-A4 samples of dose 10^{14} cm^{-2} with annealing temperature of 1000 °C and B1-B4 samples of dose 10^{13} cm^{-2} with rapid thermal annealing at 1100 °C. The C1-C4 samples do not contain S impurities.

Sulphur related luminescence of Si has been studied before (see, e.g., Refs. [17-19]), 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 [13]. Below we study effect of UST on 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 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 I).

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

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

have been determined. Here T is the temperature, k is the Boltzmann constant, q is the electron charge, n_i is the intrinsic carrier concentration, N_a is the concentration of shallow acceptors, 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

Since the samples are of DE Si, one can expect that current transport is controlled by carrier recombination. To check 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 C1 have been presented in Fig. 1 (a) and (b) for forward and reverse biases, respectively. Analysis of Fig. 1 (a) shows that for all the samples considered the J-V dependencies in forward bias are well described by the Eq. (1). Upon treating by ultrasound the electrical current J increases. It indicates that UST leads to partial inhibition of generation-recombination processes by reducing concentration of recombination active deep traps decorating the dislocations. This result is consistent with lifetime measurements [20] by open-circuit voltage decay method, which demonstrated increase of carrier lifetime.

By fitting the Eq. (1) to the measured data saturation current J_0 and ideality factor β have been determined (Table I). Analysis of Table I 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 presence of deep level defects located around dislocations.

Upon annealing by ultrasound defect spectra in all of the samples have been considerable modulated. First of all this should leave to modulation of J_0 and β. In samples A3, C3, and C4, magnitude of both J_0 and β has 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.

Analysis of current-voltage chracteristics for reverse bias (Fig. 1 (b)) showed that it can be described by 6th order polynom

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

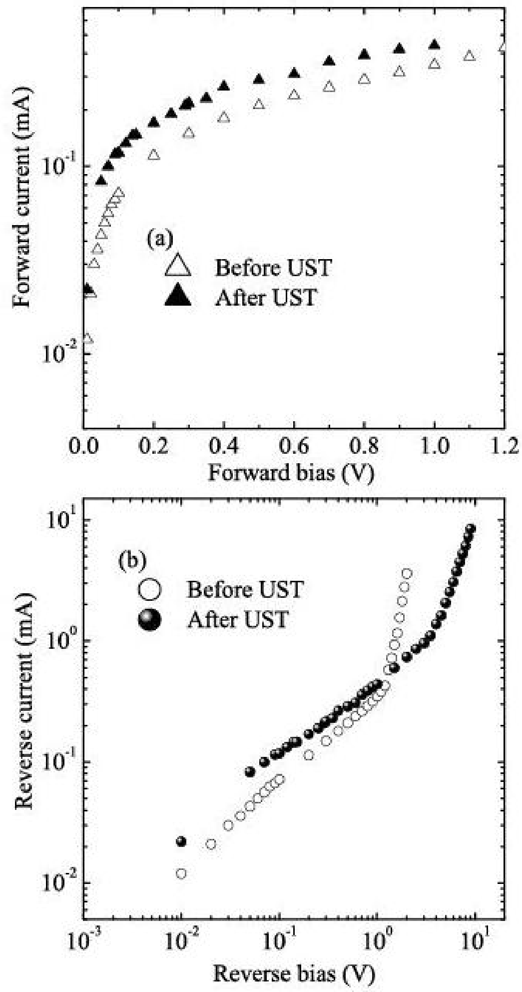

Fig. 1. Experimentally measured dark current-voltage characteristics for sample C1 for (a) forward and (b) reverse biases before (○,Δ) and after (●,▲) UST.

Here a_1-a_6 are coefficients of the polynomial determined from fitting of Eq. (3) to 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 [21] 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 each from other. Especially the difference is well defined at reverse bias larger than 1 V. One possible reason of this result could be effect of alcohol treatment of the surface. The other reason would be related to UST-stimulated modulation of the defect spectra decorating the dislocations. This reason seems more reasonable because in the light-emitting diode carrier transport is controlled by recombination activity of dislocations. The UST modulation of defects can lead to variation of the carrier concentration confined in the dislocation loops, which can be released at larger reverse voltages and contribute to the reverse current.

As noted in Ref. [3], strain field around dislocations can modulate band structure of Si. This can also affect other transport parameters such as diffusion coefficient of free carriers. This point has been discussed in our paper [22]. Estimation of the value of D from Eq. (2) is not recommended, because dependence of current on voltage is of exponential and the precision of determination of J_0 and diffusion coefficient and D would be too low.

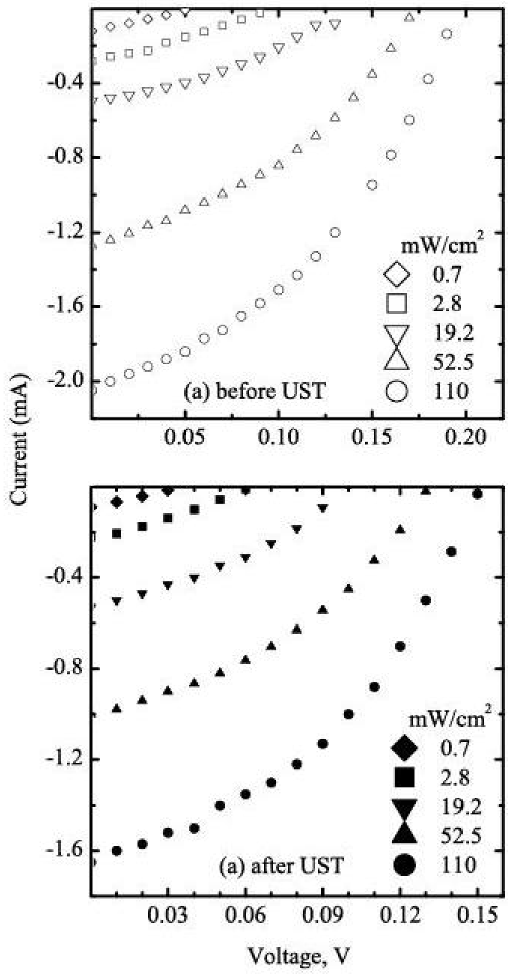

Fig. 2. Current-voltage characteristics for sample C2 (a) before and (b) after UST for different illumination intensities.

Current voltage dependence has been studied not only in the dark, but also upon illumination. From the study it is found that the samples posses photovoltaic feature. In all the samples photovoltage and photocurrent have been generated. Figure 2 displays the *J*-*V* curves corresponding to different illumination intensities. The results are presented in Fig. 2 for sample C2. To see sensitivity of the samples to variations of the illumination intensity we have plotted dependence of short-circuit current J_{sc} and open-circuit voltage V_{oc} on illumination intensity Φ (Fig. 3). It is seen that at smaller Φ both of the parameters characterizing photovoltaic feature of the samples increase sharply with increasing Φ thus demonstrating high sensitivity of the samples illumination. At larger values of Φ both J_{sc} and V_{oc} slightly increase.

Analysis of Fig. 3 (a) shows that as a result of UST magnitude of J_{sc} has been increased. The UST-induced enhancement of J_{sc} corresponds to increase of carrier lifetime. This result is consistent with that of Ref. [20] which reported about UST-induced increase of carrier lifetime for the same sample in Fig. 3 from analysis of the open-circuit voltage decay transient. The UST-induced change of the open-circuit voltage indicates that free carrier concentration has changed also. The results in Fig. 3 (a) and (b) are consistent with the ideology of this work as to UST induced transformation of defects decorating dislocations, leading to modulation of generation-recombination processes, and thus carrier lifetime, concentration and electrical current transport.

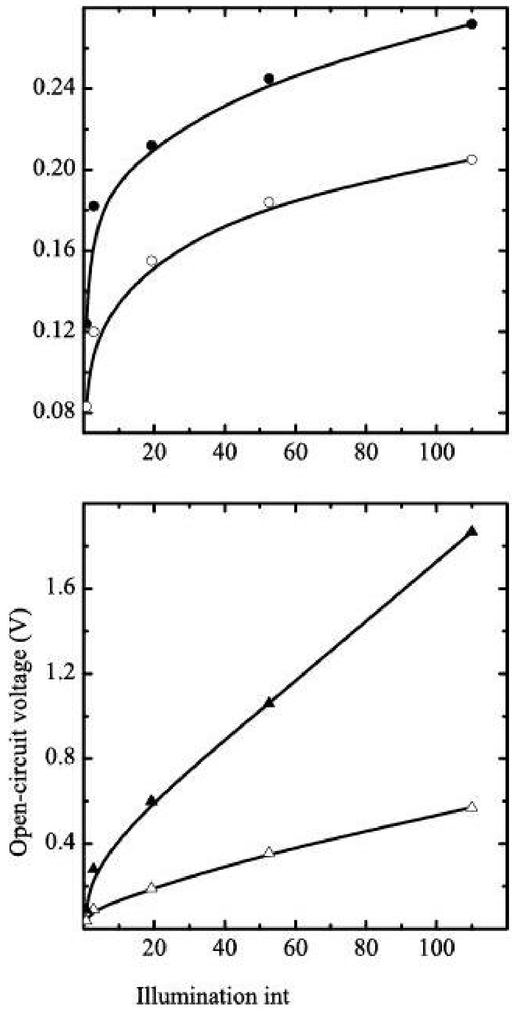

Fig. 3. Dependence of (a) photocurrent and (b) photovoltage on illumination intensity for the sample A2 before and after UST.

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 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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