Acousto--defect interaction in irradiated and non--irradiated silicon n+--p--structure

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Abstract

The experimental investigation of ultrasound influence on the electrical characteristics of silicon n+-p--structure has been carried out. The ultrasound induced effects in silicon structures, which have been exposed to reactor neutrons or 60Co gamma radiation, were studied too. It has been found out that the ultrasound loading of n+--p--structure leads to reversible change of shunt resistance, carrier lifetime, and ideality factor. Acoustically induced alteration of the ideality factor and the space charge region lifetime depends on irradiation considerably. The models of coupled defect level recombination, Shockley--Read--Hall recombination, and dislocation--induced impedance were used to describe the obtained results. The observed phenomena can deal with the increase of distance between coupled defects as well as an extension of carrier capture coefficient of complex point defects and dislocations. The results show that divacancy and pair vacancy--interstitial oxygen are effectively modified by ultrasound in contrast to interstitial carbon--interstitial oxygen complex.

Introduction

It is well known that ultrasound (US) can effectively interact with defects. As a defects engineering tool US has certain advantages:

(i)~locality of action due to the predominant absorption in regions of the lattice periodicity deviation;

(ii)~selectivity of influence, which depends on acoustic wave (AW) polarization and type;

(iii)~possibility of the defect system transformation at resonance frequency;

(iv)~capability of reversible effect in case of low intensity AW.

In piezoelectric semiconductors, the acousto--defect interaction (ADI) is determined mainly by electric field, which accompanies the vibration wave propagation. However ADI is also observed in non--piezoelectric crystals like silicon, the basic material in microelectronic. Thus it was experimentally observed that US may cause in Si structures atomic diffusion, transformation of the native and an impurity defects, modification of interior surface states, appearance of new defects. Defects are known to determine most of properties of semiconductor devices. In particular the ADI governs variation of tunneling, generation--recombination and thermionic emission currents in silicon barrier structures.

The change of population of impurity oscillator levels, the displacement of impurity atoms with respect to their surroundings, the decreasing of the diffusion activation energy, the local temperature increase by point defect clusters, the US absorption by dislocation are considered to be main mechanisms of elastic vibration--defect interaction in non--piezoelectric crystals. However to the best of our knowledge, the complete ADI theory in silicon does not exist. One of a top--ranked reasons for that is lack of experimental works, focusing on investigation of acoustically induced (AI) effects.

Not all silicon defects are acoustically active and subject to modification under US action. The ADI efficiency depends on defect type and structure. Thus, the force acting on the point defect during US loading (USL) of crystal is determined by the relaxation of the defect volume. The irradiation is most widespread and studied method of semiconductor defects alteration. On the one hand, the high--power US treatment is shown to lead to residual changes of the irradiated silicon structure properties. This effect deals with AI annealing of radiation defects (RDs). On the other hand, irradiation can be a reason of reversible AI phenomenon initiation, which is caused by formation of acoustically active RDs. Unfortunately, there are but few reports on acoustically driven phenomenon in irradiated silicon structures.

Our purpose is to investigate experimentally the AI electrical characteristic variation, which takes place in non--irradiated and irradiated n+--p-Si structures. Irradiation was carried out by reactor neutrons and a 60Co--gamma source. It is expected that γ--rays introduce VOi complex predominantly, whereas neutrons mainly create vacancy clusters, disordered regions and CiOi complex. This work represents distinction of AI effects in silicon structures with different RDs. The intensity of applied US was below the level of irreversible defect subsystem modification, which can deal with a new defect creation, a RDs annealing or a long distance (a many interatomic distance) diffusion. As a result, the full recovery of characteristics was observed after AW propagation stop. The models of coupled defect level recombination, Shockley--Read--Hall (SRH) recombination, and dislocation--induced impedance were used to describe the processes in the space charge region (SCR), in the diode base, and shunt resistance, respectively. The interaction of defects with an AW strain field was recruited to explain the observed AI phenomena. The investigation would provide not only better ADI understanding but could also facilitate the development of acoustically controlled devices or radiation sensors.

Experimental and calculation details

The 2 inch (300~μm thick) p--type boron doped, <111> orientation, Czochralski silicon wafer with resistivity of 10~Οcm was used for fabrication of n+-p--Si structure. The n+ emitter with carrier concentration of about 1019 cm-3 and thickness of 0.5~μm was formed by phosphorus implantation. Front and rear aluminium electrodes were deposited by screen printing before rapid annealing. Samples (2 cm2 area) were cut from the central part of the wafer and used in experiment. Samples were irradiated by reactor neutrons or by 60Co γ--rays. Doses D, fluences Φ, and sample labels are listed in Table Ι. Data [44,45] were used to determine D and Φ correlation. The non--ionizing energy losses (NIEL) for neutron and γ--60Co are shown in Table Ι too. Since displacement damage effect is characterized by Φ NIEL, the similar damage was expected in investigated samples. To avoid an impact of long--term annealing, which is typical to neutron damaged structure, irradiated samples have been stored for 5 years at room temperature before measuring.

The dark forward current--voltage I--V characteristics of the samples both with and without USL were measured over a temperature range of 290--340~K. The temperature was controlled by differential copper--constantan thermocouple. Some curves are shown in Fig. 1.

The double--diode model of n+--p structure I-V characteristic is expressed in the following form:

(1)

where

ISCR reflects the overall SCR recombination, I\_base is closely related to recombination in the quasi-neutral region, I\_sh is the shunt current, A is the sample area, n\_i is the intrinsic carrier concentration, tau\_g is the SCR carrier lifetime, d is the SCR thickness:

(5)

ε is the permittivity (11.7 for Si), p\_p and n\_n are the majority carrier concentration in the p-- and n--type regions, E\_g is the semiconductor band gap, N\_c and N\_v are the effective density of states in the conduction and valence bands; n\_id is the ideality factor, R\_s and R\_sh are the series and shunt resistances, mu\_n and tau\_n are the electron (minority carrier) mobility and lifetime in the diode base.

We used Eqs. (1)-(5) to fit the experimental data and tau\_g, tau\_n, n\_id, R\_sh, and R\_s were taken as the fittings parameters. The known temperature dependencies of n\_i, E\_g, and mu\_n were used. The extremely good fit to the experimental data was obtained --- see Fig. 1. In particular, the R\_s value about 1 Ohm was determined for all samples. Broken lines in Fig.1(a) demonstrate the example of calculated contributions of I\_SCR, I\_base, and I\_sh to full current.

In the USL case, the transverse AWs with frequency of 4.2~MHz were exited with help of a piezoelectric transducer and were injected in samples from the base side in the [111]--direction. The US intensities W\_US, amplitudes of lattice deformation xi\_US and lattice atom displacement u\_US are listed in Table II. It was reported previously that the characteristic time of change in the silicon structure parameters under the US action did not exceed 2 10^3 s. In order to wait till the AI transitional period the following experimental procedure has been used. After USL start the sample has been kept at room temperature during 60~min and then the I-V measurement and the sample heating were started. In order to avoid the effect of piezoelectric field on I-V characteristics, the piezoelectric transducer has been shielded.

Fig. 2 illustrates the reversibility of AI effects. The time interval between USL starting and "during" measurement was larger than 60~min, the time interval between USL stopping and "after" measurement was about 24~h. Data for nSC and g6SC are similar to those, which are presented for iSC and g7SC.

The non-linear fittings were done by using the differential evolution method.

Results and Discussion

*Space charge region*

The I-V characteristic parameters, which deal with SCR phenomena, are n\_id and tau\_g. The temperature dependences of ideality factor and SCR carrier lifetime are shown in Fig. 3 and Fig. 4, respectively.

As shown by the Fig. 3 the ideality factor decreases with temperature increase and the plot n\_id vs $1/T$ is close to linear. Thus dependence n\_id(T) can be expressed as

(6)

The thermoactivated growth of SCR lifetime is observed over the explored temperature range --- see Fig. 4. The temperature dependence of tau\_g is sufficiently described by the equation

(7)

The T\_id and E\_tau values, determined for both non--irradiated and irradiated samples under USL as well as without it are listed in Table III.

We want to stress, that

(i) irradiation leads to T\_id and E\_tau changes, the g6SC's characteristic temperature of ideality factor and SCR lifetime characteristic energy are closely related to those of g7SC under similar conditions;

(ii) USL affects n\_id and tau\_g values, the absolute AI changes of ideality factor Δn\_id=n\_idUS-n\_idin and the relative AI changes of SCR lifetime ε\_tau=(tau\_gUS-tau\_g,in)/tau\_g,in (where subscripts ''US'' and ``in'' identify the values, obtained at the same temperature with and without USL respectively) are listed in Table IV;

(iii) Δn\_id and ε\_tau vary with W\_US enhancement, whereas T\_id and E\_tau values practically do not depend on US intensity;

(iv) USL leads to increase of both T\_id and E\_tau in γ--irradiated samples (see Fig. 3(b) and Fig. 4(b)), but this effect is not observed in non--irradiated and neutron--irradiated samples (see Fig. 3(a) and Fig. 4(a));

(v) Δ n\_id and ε\_tau have an opposite sign for non--irradiated and irradiated samples (for SCg6 not in whole temperature range);

(vi) ideality factor is varied by USL more effectively in irradiated samples;

For the purpose of present consideration, it is important to discuss the recombination mechanism in the SCR of the investigated samples. According to classical SRH theory, an ideality factor must be less than 2 and tau\_g temperature dependence is expected to be described by the relation tau\_g=1/2 (where σ\_n, σ\_p, and E\_t are the electron and hole capture cross sections (CCSs) and the energy level of the recombination center, E\_i is the intrinsic energy level). In our case, n\_id is lager than 2 and tau\_g increases with temperature. Therefore SRH theory is inapplicable to the investigated samples. Several attempts to explain large n\_id value have been made with various models. But all observed features of SCR recombination (ideality factor large value, independence on light intensity, dependence on temperature as well as carrier lifetime small value) can be explained by the model of coupled defect level recombination (CDLR) only. This model provides a rapid direct charge transfer between defect levels. Such phenomenon has been observed experimentally firstly and then it was recruited to explain process in semiconductor diodes.

According to the CDLR model, recombination is the result of carrier exchange between two defect level and crystal bands. In particular, it is proposed that the recombination rate is dominated by sites where acceptor--like defect is coupled with donor-like defect. In simplified case of no carrier exchange between the donor level E\_tD and the valence band as well as between the acceptor level E\_tA and the conduction band, the recombination rate R can be expressed as

(8)

Where R\_DA is the coupling parameter, N\_D and N\_A are the densities of donor and acceptor--like defects, σ\_nD and σ\_pA are electron CCS of donor and hole CCS of acceptor, v\_th,n and v\_th,p are the thermal electron and hole velocities, n\_D,A, p\_D,A, and ε depend on E\_tD, E\_tA, and level degeneracy factors. As tau\_g~ R-1, the last three values are expected to provide a thermoactivated behavior of SCR lifetime. Unfortunately, the equation does not account for the functional relation between I-V characteristic parameters and attributes of defects, taking part in CDLR.

According to Steingrube et al., SSC for defect in a pair differs from that for isolated defect and depends on the distance between donor and acceptor r:

(9)

where C\_nD and C\_pA are constant values. Besides, R\_DA is proportional to the overlap integral of the defects wave functions. If both defects are characterized by H--like radial--symmetric wave function and equal Bohr radius a\_0, the following expression can be used:

(10)

In our opinion, the observed reversible AI n\_id and tau\_g modifications are induced by donor--acceptor distance alteration in samples under USL. Really, according to data [3], the force acting on the point defect during USL can be expressed as

(11)

where Γ is the bulk elasticity modulus, ΔΩ\_d is the crystal volume change per defect, χ is the crystal lattice deformation, and AW propagates along z axis. For interstitial atoms and substitutional impurities with ionic radius exceeding the ionic radius of matrix atoms, the ΔΩ\_d > 0, whereas, for vacancies and substitutional impurities with ionic radius smaller than the ionic radius of matrix atoms, ΔΩ\_d < 0. Therefore, a point defect vibrates under USL and oscillation amplitude and phase are determined by both the defect character and the intensity of AW.

The simplest model, which is shown in Fig. 5, gives the following qualitative conclusion. Initially donor and acceptor are separated by the distance r\_in. Axis X is drawn through point defect initial positions. Under USL defects would vibrate with amplitudes u\_D and u\_A. Vibration axis coincides with AW displacement direction and forms angle h with X--axis. The defect vibration amplitudes depend on χ\_US, defect elastic strain (ΔΩ\_dD and ΔΩ\_dΑ), defect coupling and may have different values. According to suggested model, the donor--acceptor distance in the sample under USL r\_US depends on time t:

(12)

where ω is the US cyclic frequency, δ is the phase shift between donor and acceptor vibration.

We use Eqs. (11)-(12) to estimate AI relative changes of CCS εσ=[σUS-σ(r\_in)]/\σ(r\_in) and coupling parameters ε\_RDA=[R\_DA,US-R\_DA(r\_in)]/R\_DA(r\_in), where σ and R are averaged over the AW period T\_US:

(13)

In this estimation, the relaxation time in the CDLR sub--system is assumed to be considerably less than T\_US and the previously used value a\_0=3.23 nm is applied. Besides, the chosen u\_D and u\_A values are commensurate with u\_US. But it is taken into account, that a displacement of the point defect without covalent bond could exceed a matrix atom displacement. At last, no US absorption by defect is assumed. In this simple case δ equals to 0, if (ΔΩ\_d D ΔΩ\_d A>0), or to 180, if (ΔΩ\_d D ΔΩ\_d A<0). In addition, ε\_RDA dependence on u\_D and u\_A is only determined by |u\_D-u\_A| (δ=0 case) or |u\_D+u\_A| (δ=180 case). Moreover, these dependences are identical in both cases. The typical results of simulation of coupling parameter changes are shown in Fig. 6.

ε\_σ depends on oscillation amplitudes with a similar features and does not depend on φ:

(14)

where``+'' and ``-'' correspond to δ=180 and δ=0 respectively, K\_USDA characterizes defect couple--ultrasound interaction and depends on properties defects as well as crystal matrix. It is taken into account in Eq. (15), that u\_D,u\_A ~χ\_US~W\_US.

It is worth keeping in mind, that CLDR current flows locally in the locations of extended defects. On the other hand, dislocations are often situated in the SCR region perpendicularly to p-n junction plane and investigated samples are not exception (see Section IIIC). If CDLR in the dislocation locations is assumed, then dislocations with edge component would affect the pair spatial orientation. Thus axis of donor--acceptor pair with ( ΔΩ\_d D ΔΩ\_d A>0)$ should be predominantly parallel to dislocation line, whereas the axis of the pair of coupled defects with ΔΩ\_d D ΔΩ\_d A<0 should make a right angle with it. As AW displacement is parallel to the p-n junction plane, the cases of most exciting interest are following:

δ=0...

In other words, all curves in Fig. 6 can be realized if defect volume relaxation of donor--like defect has the sign opposite to that of acceptor--like defect. And only squares have to be under consideration in ΔΩ\_d D ΔΩ\_d A>0 case.

Taking into account the experimental results and suggested model estimation:

(i) E\_tau and T\_id$ are mainly determined by couple component energy levels. The alteration of E\_tau and T\_id for nSC, g6SC, and g7SC in comparison with iSC testifies on the change of defect (donor, acceptor, or both), which take part in CDLR, after irradiation. And g6SC defect is coincident to g7SC defect and differs from neutron--irradiated sample defect.

(ii) USL causes donor--acceptor distance change and results in ε\_σ and ε\_RDA, which increase with W\_US.

(iii) Acoustically induced E\_tau and T\_id modification, which is observed in g6SC, and g7SC only, testifies on the rebuilding of γ-induced RD. I.e., γ--induced RD is conﬁgurationally bistable (or metastable) and transforms from ground state to another under US action. Similar AI defect variations were also reported reviously.

(iv) ε\_σ sign is immutable --- see Eq. 15, whereas ε\_RDA sign can vary for a pair with opposite relaxation volume component (see Fig. 6). Therefore Δ n\_id and ε\_tau sign change is an evidence of transformation from (ΔΩ\_d D ΔΩ\_d A>0) to (ΔΩ\_d D ΔΩ\_d A<0) after irradiation. Transformation is confirmed by rise of US influence efficiency in irradiated samples. Really, in the case of to (ΔΩ\_d D ΔΩ\_d A<0) the US efficiency is determined by the sum of pair component displacements, whereas in the contrary case --- by their difference. Conceivably, both donor and acceptor are of interstitial--type in non--irradiated sample, and one of pair component is of vacancy--type in irradiated samples. The defect configuration are discussed below, in Section IID.

*Quasi--neutral region*

Base lifetime mirrors the processes, which occur in the quasi--neutral region of p-n--structure. Fig. 7 shows the tau\_n behaviour in the explored temperature range. Minority carrier lifetime expectedly rises with temperature increase and tau\_n values equal to 2-5 μs for different samples at 320~K. These values correspond to 80-130 μm range of diffusion length. In our opinion, the observed tau\_n dispersion is not defined by irradiation, but deals with sample--ancestor wafer inhomogeneity, which is revealed quite often.

Really, the irradiation induced lifetime reduction is described by the Messenger–-Spratt equation:

(16)

where tau\_n0 is the minority carrier lifetime in the non--irradiated sample, and K\_tau is a lifetime damage--constants. The known K\_\tau values and estimated changes of reciprocal base lifetime K\_tauΦ are shown in the Table V. It shows, that the estimated value of radiation--induced tau\_n-1 change equals to 8-17, 4, and 29 % of its measured value for samples nSC, g6SC, and g7SC respectively, and cannot explain dispersion observed experimentally. Calculated lifetime changes K\_tauΦ are in quite good agreement with those, which are expected from RDs production --- see Section ΙΙΙD.

Base lifetime can be expressed as following:

(18)

Where tau\_bb, tau\_CE, tau\_SRH are the lifetimes of band--to--band, Coloumb--enhanced Auger, and SRH recombination, respectively. Calculation shows, that tau\_bb=14 s, tau\_CE=7 s and can be neglected. In case of low injection level and single recombination centre, SRH lifetime is described by Eq. (10). If there are several centers of recombination the following equation should be applied

(19)

Where M\_d is the total number of centers, tau\_n,i characterizes lifetime due to recombination by i-th defect, N\_d,i and σ\_n,i are the concentration and electron CCS of i-th defect, respectively.

Fig. 7 shows, that USL results in tau\_n decrease. Relative AI changes of reciprocal base lifetime ε\_tau n=(tau\_n,in-tau\_nUS)/tau\_nUS are listed in Table IV. As AI changes is reversible, in our opinion, this effect deals with increase of σ\_n under US action. Following the empirical relation proposed by Ref. 65, we assume that Eq. (11) is correct for complex point defect too. But in this case, r is the distance, which separates components of complex. According to the model suggested in Section IIIA, USL leads to r variation and σ\_n change in line with Eq. (15). In case of CDLR, AI change of donor (or/and acceptor) SSC is supplemental to variation of both the coupling parameter and the couple distance. But only change of SSC determines the AI variation of base lifetime.

On the other hand, not every defect effectively takes part in AID. If M\_dAA and M\_dnonAA are the total numbers of acoustically active (AA) and non--AA center, Eq (18) for tau\_n-1 under USL and without it takes the following shape

(20)

Using Eq (15), ε\_taun transforms as follows

(21)

where K\_USeff characterizes ADI in the sample and depends on concentration of both AA and non--AA centers

(22)

K\_US,j deals with j--th defect--ultrasound interaction.

The obtained dependences ε\_taun vs W\_US are shown in Fig. 8. Linearity of these dependencies prove correctness of our assumptions. The determined K\_USeff values are listed in the Table V. The non--monotonic K\_USeff alteration with γ dose is discussed in Section IIID.

*Shunt resistance*

Fig. 9 shows the shunt resistance over the explored temperature range. One can see, that irradiation results in R\_sh decrease. Besides the R\_sh temperature dependence behavior is changed in γ-exposed samples. In particular the shunt resistance decreases with the temperature growth in iSC and nSC, whereas close to linear increase of R\_sh vs T is observed in g6SC and g7SC at 293~K neighbourhood. We want to notice that R\_sh axis is logarithmic in Fig. 9(a) and linear in Fig. 9(b).

Several non-mechanical reasons of p--n structure shunt resistance appearance are known. They are aluminum particles, macroscopic Si3N4 inclusions, inversion layers at precipitates. So in the course of firing Al particle may penetrate into the sample creating p+--doped region around it, which compensates the emitter and stay in ohmic contact with the base. Inversion layers and Si3N4 inclusions occur in multicrystalline silicon cells mainly and cannot cause a shunt resistance of investigated samples. In addition, dislocations, which intersect the junction, are generally held responsible as a possible source of ohmic current. In our opinion, both aluminum particles and dislocations are present in the investigated structure. The overall shunt resistance can be expressed as

(23)

Where R\_shAl and $R\_shdis deal with aluminum particles and dislocations, respectively. The linear temperature dependence of metal particles R\_shAl is suggested:

(24)

where R\_293Al is the shunt resistance at 293 K and α is the resistance temperature coefficient.

Gopal and Gupta introduced the model of dislocation--induced impedance of photovoltaic detector. According to this model, the R\_sh,dis can be given by

(25)

with

(26)

where E\_dis is the energy level which significantly contributes to the dislocation recombination current, U\_s is the potential at the surface of the dislocation core, ρ\_dis and A\_dis are the dislocation density and surface area, respectively, K\_n and K\_p are the capture probabilities for electrons and holes by the dislocation states, N\_dis is the density of surface states at each dislocation. Eq. (23) is correct in simplified case of K\_p=K\_n.

α was determined from g7SC data. Obtained value 8.3 K is not far from resistance temperature coefficient of bulk Al (4.3 K). Then we used Eqs. (21)-(23) to fit the experimental R\_sh data. R\_293Al, (E\_dis-E\_i), U\_s, and σ\_dis were taken as the fitting parameters. It was established that the experimental data are in good agreement with the fitting curves (see Fig. 9) for values (E\_dis-E\_i)=0.46 eV and U\_s=5 eV, which were independent of irradiation and USL. The obtained value of (E\_dis-E\_i) corresponds to the carrier activation energy 0.10 eV. This value is comparable to the activation energy of dislocation levels 0.08 eV, which was early reported [24] in Cz--Si:B too [23].

Obtained values of R\_293Al and σ\_dis are listed in the Table III. R\_293Al does not depend on USL and increases with irradiation level. In our opinion, R\_shdis is less than R\_shAl in iSC. Irradiation leads to vacancy production and Al diffusion out of electrodes. As a result, the quantity of Al particles rises, R\_shAl decreases and becomes the key factor of overall shunt resistance value. The Al diffusion is more effective in γ--exposed samples due to more uniform distribution of irradiation--induced single vacancies.

Dispersions of σ\_dis and tau\_n correlate on samples set. Hence it deals with wafer inhomogeneity too. USL leads to σ\_dis increase, relative AI changes ε\_σdis=(σ\_dis,US-σ\_dis,in)/σ\_dis,in are shown in the Table IV. In our opinion this is caused by an A\_dis augmentation. Namely, the dislocation core atom displacement is normal to the current direction. As the result, carriers are captured by dislocation levels from enlarged volume. Therefore the effective surface area increases and R\_shdis decreases under US action.

*Defect type speculation*

Lifetime killers in boron--doped Czochralski--grown Si are the boron--oxygen related (BO) defects, iron--boron pairs (or another Fe--related trap in the n+-p--junctions), and oxide precipitates. The first two defects are sensitive to intensive illumination at room temperature. To determine the major recombination center of investigated samples the following experimental procedure has been used. The non-irradiated sample was light soaked under halogen lamp (2 Suns) illumination at approximately 305 K. The illumination varied from 1 h to 8 h. After illumination sample is stored in the dark at room temperature. To determine the kinetics of parameters the I-V characteristics have been measured with interval 10—15 min at room temperature over a period 5 h after illumination stopping. To determine the permanent light--induced change the I-V characteristics have been measured in 48 h after illumination. After accumulated time under illumination had run up to 15 h the iSC was annealed at 200 C for 10 min in the dark and measurements were made at room temperature. After that, the illumination and measurements were repeated.

Intensive light is known to lead to permanent transformation of BO defects and considerable decrease of minority--carrier lifetime (down to 10 \% of initial value at long term illumination). Annealing at 200 C for 10 min in the dark results in both BO defects state recovery and readiness of light--induced degradation. Fig. 10 show changes of structure parameters in comparison with those before illumination. One can see that illumination did not result in considerable permanent change of either of the tau\_g, tau\_n, n\_id before as well as after annealing. Therefore BO influence on recombination can be neglected in both the SCR and the base.

On the other hand, the vast majority of impurity iron exists in iron--boron pairs. FeiBs can be readily dissociated under intense illumination to release interstitial iron. This gives a lifetime change. In dark FeiBs repairing takes place and Fei concentration decreases according to

(27)

where N\_Fe0 and N\_Feeq are the concentration after illumination immediately and equilibrium concentration which remains a long time after dissociation respectively, and the characteristic time of repairing tau\_rep depends on doping level

(28)

E\_DFe=0.68 eV is the activation energy of Fei diffusion.

n\_id increase (about 0.03) and tau\_g decrease (about 10 \%) immediately after illumination were observed --- see Fig. 11(a). These changes vanished gradually. We supposed that the tau\_g and n\_id evolutions could be described by expressions, which like to Eq. (25). Then Eq. (26) was used to calculate characteristic time and fitting lines were plotted on Fig. 12(a). The fittings with E\_DFe=0.68 eV are in good agreement with experimental data. Hence iron--boron pairs take part in SCR recombination. On the other hand, electron and hole CCS of Fei are 1.7 and 0.04 times as much as those of FeiBs. A small (about 10 \%) tau\_g alteration, which is caused by light, is evidence of supporting role of iron--boron pair in SCR recombination. Furthermore, since tau\_n does not depend on illumination (see Fig. 12(b)), then FeiBs does not influence on base lifetime.

As a result, oxide precipitates are number one in SCR and base recombination. According to Murphy, at least two independent oxide precipitate related defects exist. These defects have σ\_n/σ\_p=157 and σ\_p/σ\_n=1200 respectively. So, they are suitable for CDLR. On the basis of mentioned above, we conclude that the defect, responsible for AI phenomena in nSC, is oxide precipitate mainly.

It is worth keeping doping level, oxygen concentration and irradiation dose in mind when RD type is foreseen. In our case (Czochralski, oxygen--rich, 717 cm3, p--Si with boron concentration 1015 cm3 and low dose) it is expected, that CiOi, vacancy clusters Vn (divacancy V2, trivacancy V3, ...) and VOi are produced mainly by neutron irradiation and CiOi and VOi by γ--rays. The RD concentration N\_tRD is proportionate to dose, the known introduction rate for neutron η\_n and gamma η\_γ irradiation in Cz--Si are shown in the Table VI. The expected values of N\_tRD for investigated samples are listed in the Table VI too.

Another defects, which can be created by irradiation in silicon, are I\_p--center, bistable donor (BD), B\_iO\_i and C\_iC\_s. But I\_p--center and BD are characterized by small introduction rate. For example, expected concentration of BD is only 1 1010 cm3 in nSC and g7SC. The lack of B\_iO\_i in investigated samples deals with low boron concentration . Lastly, C\_iC\_s creation is suppressed in oxygen--rich crystal. Besides C\_iC\_s is not recombination active center.

The influence of RD on base lifetime could be estimated by Eq. (18) taking into account the fact, that VO\_i is not active recombination center in p--Si. Estimated tau\_nRD for CiOi, V2, and V\_3 are shown in Table VI. It shows that tau\_n is effected mainly by CiOi and vacancy clusters in $\gamma$-- and neutron--irradiated samples, respectively. It should be noted, that nSC, g6SC, g7SC sums of tau\_nRD are in quite good agreement with K\_tauΦ values.

Lets consider K\_USeff assuming that M\_dAA=1, M\_dnonAA=1 in non--irradiated sample and US interaction with CiOi and Vn is described by K\_USCO and K\_USV, respectively. Then Eq. (20) gives the following expression for K\_USeff in nSC and irradiated samples:

(34)

tau\_AA is the base lifetime of the sample, where non-radiative AA defect with K\_USAA is present only.

Two extreme cases are opportune for analysis. In the first one, non--AA defects are distributed uniformly across the wafer and AA defects define a distinction of (tau\_nin-K\_tauΦ) values in different samples. In the second one, a non--AA defect distribution is not uniform, whereas tau\_ninAA is identical for iSC, nSC, g6SC, and g7SC. However, in the first case (as well as in case of M\_dnonAA=0), experimental K\_USeff values lead to unreal (negative) values of K\_USj. In the second case, Eq. (41) and the data from the Tables VI and V, give the following array equations:

(45)

where tau\_ninAA in 104 s. These equations are correct if K\_USAA=10 W, K\_USV=42 W, K\_USCO=0. Since tau\_nin <1.83, then K\_USAA>5 cm2. Thus observed change of the base lifetime is caused by AI modification of the same defect (most likely oxide precipitates) in both non--irradiated and $\gamma$--irradiated samples. This effect is added by AI divacancy alteration in neutron--irradiated samples. In other words, CiOi is non--AA defect, whereas V\_2 is AA defect.

As to SCR recombination, in our judgement, tau\_g and n\_id in non--irradiated sample are affected by modification of coupled oxide precipitate related defects under US action. As assumed above in Section IIIA, the AA radiation defects with ΔΩ\_d<0 take part in CDLR in irradiated samples. Divacancy is quite suitable explanation for AI influence on tau\_g and n\_id in nSC. But in γ--irradiated samples a bistable (or metastable) defect is expected. Few such defects with ΔΩ\_d<0 are known in Si, viz VO\_2, V\_3, and VO\_i. VO\_2 appears after 300 C annealing of irradiated crystal, V\_3 is not typical defect for γ-60Co exposed silicon. On the other hand, VO\_i is largo manum produced and can take part in CDLR around n^+-p interface in g6SC and g7SC. Metastable state, which is commonly observed at low temperature, is remarkable for the large oxygen--vacancy distance and more deep energy level. The volume change of entire complex is negative, whereas for the complex component ΔΩ\_d<0 and ΔΩ\_d>0. Hence, under made assumption, VO\_i is favorable pair for AI alteration of distance between component. Thus VO\_i can be transformed into metastable configuration by USL and this effect results in both T\_id and E\_tau change.

Conclusion

The experimental investigation of ultrasound influence on the I-V characteristic of silicon n^+-p--structure has been carried out. The ultrasound induced effects in silicon structures, which have been exposed to reactor neutrons or 60Co gamma radiation, were studied too. The investigation revealed the acoustically driven reversible decrease of both the minority carrier lifetime in a structure base and the shunt resistance. The effect intensifies in irradiated structures. The analysis shows that the acoustically induced increase of carrier capture coefficient of point or extended defects is a reason of observed effects. It has been found out that the ultrasound loading leads to the reversible modification of SCR carrier lifetime and ideality factor. Changes are opposite in sign in non--irradiated and irradiated structures. The qualitative model of observed phenomenon, which is based on the increase of a distance between coupled defects or between defect complex components under ultrasound action, was considered. It has been shown that divacancy and pair vacancy--interstitial oxygen are effectively modified by ultrasound in neutron-- and γ--exposed structures respectively. Interstitial carbon--interstitial oxygen complex does not practically take part in acousto--defect interaction. Thus, ultrasound can be an effective tool for controlling silicon structure characteristics.

Tabs captions.

Tab I. The sample irradiation parameters.

Tab.II The ultrasound loading parameters.

Tab III. Characteristics of temperature dependences of n+-p--Si structure parameters.

Tab IV. Acoustically induced change of n+-p-Si structure parameters (at 330~K).

Tab V. Measured and estimated base lifetime parameters.

Tab VI. Cited and calculated defect parameters.

Figure captions

Fig.1 Dark I-V characteristics measured (a) at 306~K for non--irradiated (circles), neutron--irradiated (squares) and gamma--irradiated (diamonds and triangles) structures without USL; (b) at 301~K (circles) and 341~K (asterisks) with (filled marks, Ui--2) and without (open marks) USL for the iSC. The marks are the experimental results, the solid lines are the fitted curves using Eqs. (1)-(5). The dashed, dotted and dot--dashed lines in (a) represent the calculated base, SCR and shunt components of full (black solid line) iSC current.

Fig.2 SCR lifetime (a, left axis, open marks), base lifetime (a, right axis, filled marks), ideality factor (b, left axis, open marks) and shunt resistance (b, right axis, filled marks), obtained before, during and after USL at 330~K. Data for iSC (circles) and g7SC (triangles) are presented.

Fig.3. Temperature dependences of ideality factor for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and γ--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq.~(2).

Fig.4 Temperature dependences of SCR lifetime for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and $\gamma$--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq. (7).

Fig.5 Model of CDLR center behavior under US action.

Fig.6 Simulated dependencies of AI changes of coupling parameter on the vibration amplitudes. Axis|u\_D-u\_A| corresponds to δ=0 case, whereas axis |u\_D+u\_A| corresponds to δ=180 case. The parameters are set to a\_0=3.23 nm, r\_in=5 nm (open marks), 15 nm (semi--filled marks), and 25 nm (filled marks), φ=0 (circles), 90 (squares). Triangles correspond to mean ε\_RDA value for [0, 180] φ range.

Fig 7. Temperature dependences of base lifetime for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and $\gamma$--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively.

Fig 8. Dependences of base lifetime relative change on US intensity for non--irradiated (circles), neutron--irradiated (squares), and γ—irradiated (triangles and diamonds) samples. Lines are the fitted curves using Eq. (19).

Fig 9. Temperature dependences of shunt resistance for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and γ--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq. (21)-(23).

Fig10. Permanent changes of SCR lifetime (a, squares), ideality factor (b, circles), base lifetime (c, triangles), and shunt resistance (d, asterisks) versus accumulated illumination time. Sample iSC, T=295 K. Filled, semi--filled and open marks correspond to sample before annealing, after first 10 min 200 C annealing, and after second 10 min 200C annealing, respectively.

Fig.11. SCR lifetime (a, squares, left axis), ideality factor (a, circles, right axis), base lifetime (b, triangles, left axis), and shunt resistance (b, asterisks, right axis) as a function of time since illumination stoping. Sample iSC, T=295 K. Lines are calculated by using Eqs.(25)--(26) and E\_DFe=0.63 eV (dash--dotted lines), 0.68~eV (solid lines), and 0.73~eV (dashed lines).