

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

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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 ^{60}Co 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.

Keywords: acousto-defect interaction, silicon, irradiation

I. 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,^{1,2} transformation of the native and an impurity defects,³⁻⁷ modification of interior surface states,⁸⁻¹⁰ appearance of new defects.^{11,12} Defects are known to determine most of properties of semiconductor devices. In particular the ADI governs variation of tunneling,^{13,14} generation-recombination¹⁵⁻¹⁷ and thermionic emission^{18,19} currents in silicon barrier structures.

The change of population of impurity oscillator levels,²⁰ the displacement of impurity atoms with respect to their surroundings,^{4,21,22} the decreasing of the diffusion activation energy,²³ the local temperature increase by point defect clusters,²⁴ the US absorption by dislocation^{16,25,26} 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.⁸ Thus, the force acting on the point defect during US loading (USL) of crystal is determined by the relaxation of the defect volume^{21,22}. The irradiation is most widespread and studied method of semiconductor defects alteration. On the one hand, the high-power US treatment is shown²⁷⁻³⁰ 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,^{31,32} 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 ^{60}Co -gamma source. It is expected that γ -rays introduce VO_i complex predominantly,³³⁻³⁵ whereas neutrons mainly create vacancy clusters,^{36,37} disordered regions³⁸ and C_iO_i complex.^{35,39} 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,^{40,41} Shockley-Read-Hall (SRH) recombination, and dislocation-induced impedance^{42,43} were used to describe the processes in the space charge region (SCR), in the diode base, and shunt resistance, re-

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TABLE I. The sample irradiation parameters.

Sample	Irradiation type	D (rad)	Ψ (cm ⁻²)	NIEL ^a (MeV cm ² /g)	$\Psi \times \text{NIEL}$ (MeV/g)
iSC	non	0	0	—	0
nSC	neutron	$4.5 \cdot 10^3$	$4 \cdot 10^{11}$	$2.04 \cdot 10^{-3}$	$8.2 \cdot 10^8$
g6SC	γ - ⁶⁰ Co	$1 \cdot 10^6$	$1.6 \cdot 10^{15}$	$1.07 \cdot 10^{-7}$	$1.7 \cdot 10^8$
g7SC	γ - ⁶⁰ Co	$1 \cdot 10^7$	$1.6 \cdot 10^{16}$	$1.07 \cdot 10^{-7}$	$1.7 \cdot 10^9$

^a Ref. 44.

spectively. The interaction of defects with an AW strain field^{21,22} 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.

II. EXPERIMENTAL AND CALCULATION DETAILS

The 2 inch (300 μm thick) p-type boron doped, <111> orientation, Czochralski silicon wafer with resistivity of 10 $\Omega \cdot \text{cm}$ was used for fabrication of n^+ -p-Si structure. The n^+ emitter with carrier concentration of about 10^{19} 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 Ψ , and sample labels are listed in Table I. Data^{44,45} were used to determine D and Ψ correlation. The non-ionizing energy losses (NIEL) for neutron and γ -⁶⁰Co are shown in Table I too. Since displacement damage effect is characterized by ($\Psi \cdot \text{NIEL}$), the similar damage was expected in investigated samples. To avoid an impact of long-term annealing, which is typical to neutron damaged structure,^{35,36} 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:

$$I(V, T) = I_{SCR} + I_{base} + I_{sh}, \quad (1)$$

$$I_{SCR} = \frac{qAn_id}{2\tau_g} \left\{ \exp \left[\frac{q(V - IR_s)}{n_{id}kT} \right] - 1 \right\}, \quad (2)$$

$$I_{base} = \frac{qAn_i^2}{p_p} \sqrt{\frac{\mu_n kT}{\tau_n}} \left\{ \exp \left[\frac{q(V - IR_s)}{kT} \right] - 1 \right\}, \quad (3)$$

$$I_{sh} = (V - IR_s)/R_{sh}, \quad (4)$$

where I_{SCR} reflects the overall SCR recombination, I_{base}

TABLE II. The ultrasound loading parameters.

Sample	W_{us} (W/cm ²)	ξ_{us} (10 ⁻⁶)	u_{us} (nm)	USL label
iSC	0.22	3.1	0.67	Ui-1
	0.40	4.2	0.91	Ui-2
nSC	0.24	3.2	0.70	Un-1
	0.40	4.2	0.91	Un-2
g6SC	0.38	4.1	0.89	Ug6-2
g7SC	0.19	2.9	0.63	Ug7-1
	0.37	4.0	0.87	Ug7-2

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, τ_g is the SCR carrier lifetime, d is the SCR thickness:

$$d = \sqrt{\frac{2\epsilon\epsilon_0}{qp_p} \left[\frac{E_g}{q} - \frac{kT}{q} \ln \left(\frac{N_v N_c}{p_p n_n} \right) - \frac{2kT}{q} - V \right]}, \quad (5)$$

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, μ_n and τ_n are the electron (minority carrier) mobility and lifetime in the diode base.

We used Eqs. (1)–(5) to fit the experimental data and τ_g , τ_n , n_{id} , R_{sh} , and R_s were taken as the fittings parameters. The known^{46–48} temperature dependencies of n_i , E_g , and μ_n were used. The extremely good fit to the experimental data was obtained — see Fig. 1. In particular, the R_s value about 1 Ω 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 excited 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 ξ_{us} and lattice atom displacement u_{us} are listed in Table II. It was reported previously^{6,7,19} that the characteristic time of change in the silicon structure parameters under the US action did not exceed $2 \cdot 10^3$ 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.⁴⁹

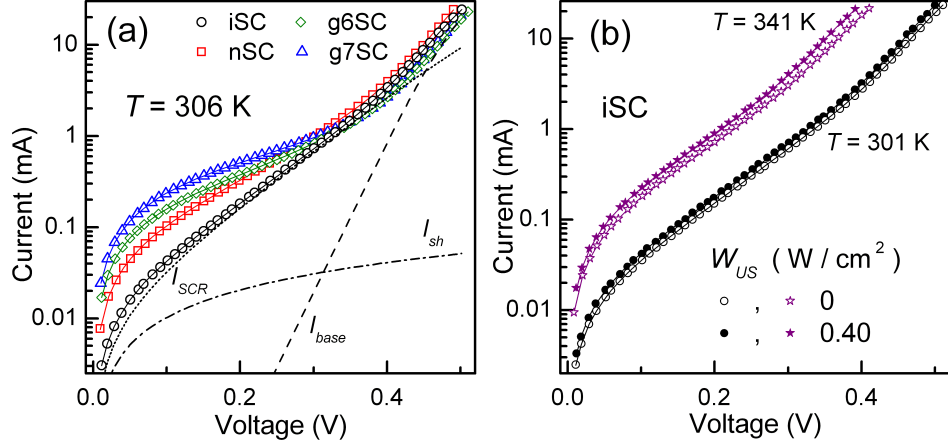


FIG. 1. Dark I - V characteristics measured (a) at 306 K for non-irradiated (circles), neutron-irradiated (squares) and gamma-irradiated (diamonds and triangles) structures without USL; (b) at 301 K (circles) and 341 K (asterisks) with (filled marks, Ui-2) and without (open marks) USL for the iSC. The 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.

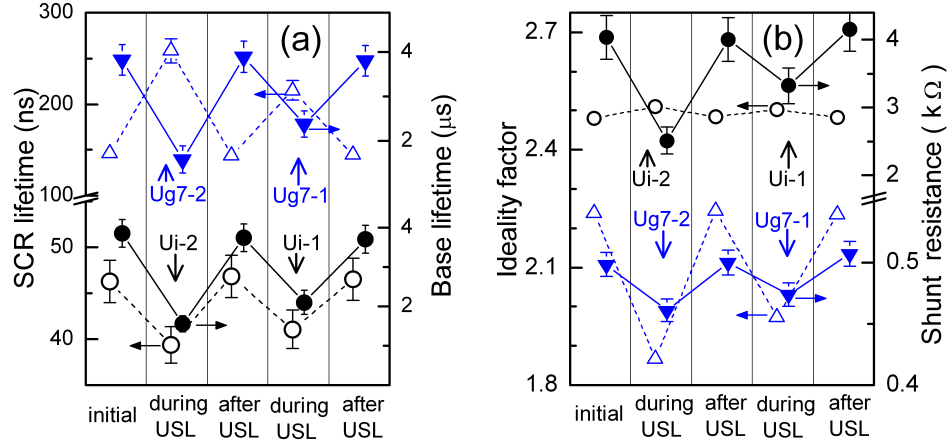


FIG. 2. SCR lifetime (a, left axis, open marks), base lifetime (a, right axis, filled marks), ideality factor (b, left axis, open marks) and shunt resistance (b, right axis, filled marks), obtained before, during and after USL at 330 K. Data for iSC (circles) and g7SC (triangles) are presented.

III. RESULTS AND DISCUSSION

A. Space charge region

The I - V characteristic parameters, which deal with SCR phenomena, are n_{id} and τ_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

$$n_{id}(T) = n_{id,\infty} + T_{id}/T. \quad (6)$$

The thermoactivated growth of SCR lifetime is observed over the explored temperature range — see Fig. 4. The

temperature dependence of τ_g is sufficiently described by the equation

$$\tau_g(T) = \tau_{g0} \exp\left(-\frac{E_{\tau g}}{kT}\right). \quad (7)$$

The T_{id} and $E_{\tau g}$ 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 $E_{\tau g}$ 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 τ_g values, the absolute AI changes of ideality factor $\Delta n_{id} = n_{id,us} - n_{id,in}$ and the relative AI changes of SCR lifetime $\varepsilon_{\tau g} = (\tau_{g,us} - \tau_{g,in})/\tau_{g,in}$

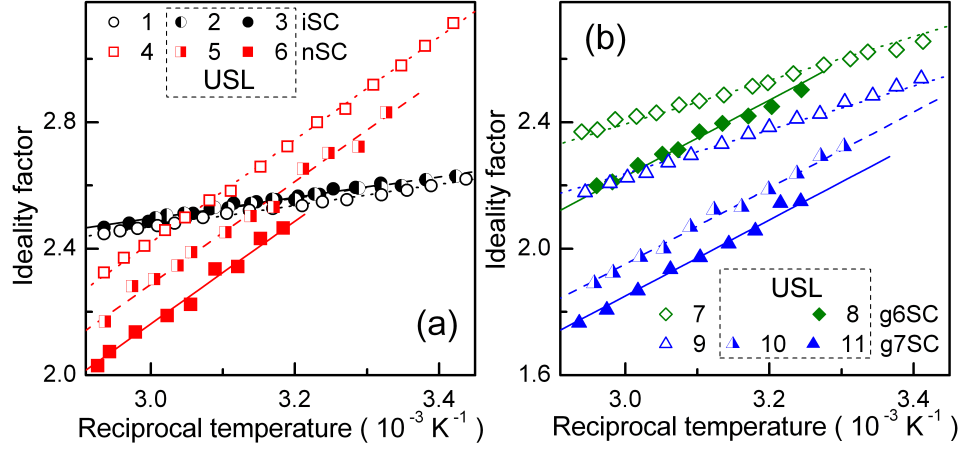


FIG. 3. Temperature dependences of ideality factor for non-irradiated (curves 1–3, circles), neutron-irradiated (4–6, squares) and γ -irradiated (7–11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui-1, 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. (6).

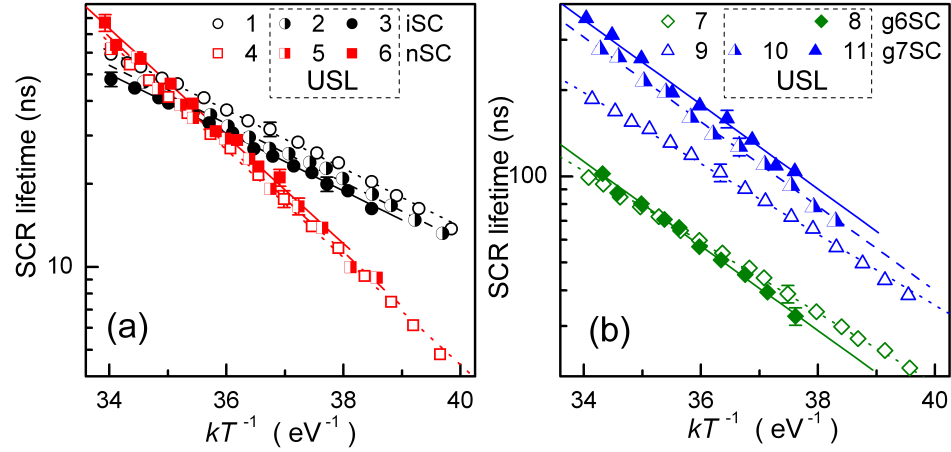


FIG. 4. Temperature dependences of SCR lifetime for non-irradiated (curves 1–3, circles), neutron-irradiated (4–6, squares) and γ -irradiated (7–11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui-1, Ui-2, 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. (7).

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

Sample	USL	T_{id} (K)	$E_{\tau g}$ (eV)	$R_{293,A1}$ (k Ω)	σ_{dis} (10^4 K/ Ω)
iSC	non	330 ± 30	0.24 ± 0.01	27 ± 3	41 ± 4
	Ui-1	310 ± 30	0.24 ± 0.01	27 ± 3	50 ± 4
	Ui-2	360 ± 30	0.24 ± 0.01	26 ± 3	58 ± 4
nSC	non	1610 ± 70	0.45 ± 0.02	2.2 ± 0.4	65 ± 7
	Un-1	1600 ± 70	0.44 ± 0.02	2.3 ± 0.4	95 ± 10
	Un-2	1680 ± 70	0.44 ± 0.02	2.2 ± 0.4	130 ± 10
g6SC	non	610 ± 40	0.28 ± 0.01	0.7 ± 0.1	19 ± 2
	Ug6-2	1080 ± 50	0.33 ± 0.02	0.8 ± 0.1	24 ± 2
g7SC	non	770 ± 50	0.29 ± 0.01	0.41 ± 0.06	26 ± 3
	Ug7-1	1260 ± 60	0.34 ± 0.02	0.39 ± 0.06	45 ± 4
	Ug7-2	1270 ± 60	0.35 ± 0.02	0.38 ± 0.06	55 ± 4

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

Sample	USL	Δn_{id} (± 0.01)	$\varepsilon_{\tau g}$ ($\pm 5\%$)	$\varepsilon_{\tau n}$ (± 0.2)	$\varepsilon_{\sigma dis}$ ($\pm 10\%$)
iSC	Ui-1	0.02	-14	0.7	20
	Ui-2	0.03	-17	1.4	40
nSC	Un-1	-0.13	5	1.5	50
	Un-2	-0.26	13	3.0	100
g6SC	Ug6-2	-0.15	2	2.3	30
g7SC	Ug7-1	-0.26	49	0.9	70
	Ug7-2	-0.36	70	1.9	110

(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 $\varepsilon_{\tau g}$ vary with W_{US} enhancement, whereas T_{id} and $E_{\tau g}$ values practically do not depend on US intensity;

(iv) USL leads to increase of both T_{id} and $E_{\tau g}$ 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) Δn_{id} and $\varepsilon_{\tau g}$ 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 τ_g temperature dependence is expected^{50,51} to be described by the relation $\tau_g \simeq 2\tau_n \sqrt{\sigma_n/\sigma_p} \cosh[(E_t - E_i)/kT]$ (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 larger than 2 and τ_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.^{52–55} 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)^{40,41} only. This model provides a rapid direct charge transfer between defect levels. Such phenomenon has been observed experimentally firstly^{56,57} and then it was recruited to explain process in semiconductor diodes.^{40,41,58}

According to the CDLR model, recombination is the result of carrier exchange between two defect level and crystal bands. In particular, it is proposed⁴¹ 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_t^D and the valence band as well as between the acceptor level

E_t^A and the conduction band, the recombination rate R can be expressed⁴⁰ as

$$R = \frac{R_{12} - \sqrt{R_{12}^2 - 4\tau_n^D \tau_p^A (np - n_i^2)(1 - \epsilon)}}{2\tau_n^D \tau_p^A (1 - \epsilon)}, \quad (8)$$

$$R_{12} = \frac{(n + n_D)(p + p_A)}{R_{DA}} + \tau_n^D(p + p_D) + \tau_p^A(n + n_A), \quad (9)$$

$$\tau_n^D = (N_D \sigma_n^D v_{th,n})^{-1}, \quad \tau_p^A = (N_A \sigma_p^A v_{th,p})^{-1}, \quad (10)$$

where R_{DA} is the coupling parameter, N_D and N_A are the densities of donor and acceptor-like defects, σ_n^D and σ_p^A 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_t^D , E_t^A , and level degeneracy factors. As $\tau_g \propto R^{-1}$, 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.*⁴¹, SSC for defect in a pair differs from that for isolated defect and depends on the distance between donor and acceptor r :

$$\sigma_{n,p}^{D,A}(r) = C_{n,p}^{D,A} r^2, \quad (11)$$

where C_n^D and C_p^A 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:⁴¹

$$R_{DA}(r) \propto N_D N_A \left[1 + \frac{r}{a_0} + \frac{1}{3} \left(\frac{r}{a_0} \right)^2 \right] e^{-r/a_0}. \quad (12)$$

In our opinion, the observed reversible AI n_{id} and τ_g modifications are induced by donor-acceptor distance alteration in samples under USL. Really, according to data,^{21,22} the force acting on the point defect during USL can be expressed as

$$F_d = \chi \Delta \Omega_d \frac{\partial \xi(z, t)}{\partial z}, \quad (13)$$

where χ is the bulk elasticity modulus, $\Delta \Omega_d$ is the crystal volume change per defect, ξ is the crystal lattice deformation, and AW propagates along z axis, $\partial \xi(z, t)/\partial z \propto \xi_{US}$. For interstitial atoms and substitutional impurities with ionic radius exceeding the ionic radius of matrix atoms, the $\Delta \Omega_d > 0$, whereas, for vacancies and substitutional impurities with ionic radius smaller than the ionic radius of matrix atoms, $\Delta \Omega_d < 0$. 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

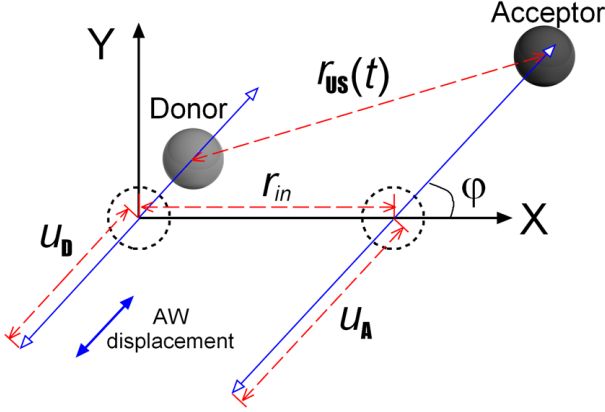


FIG. 5. Model of CDLR center behavior under US action.

defects would vibrate with amplitudes u_D and u_A . Vibration axis coincides with AW displacement direction and forms angle φ with X-axis. The defect vibration amplitudes depend on ξ_{US} , defect elastic strain ($\Delta\Omega_d^D$ and $\Delta\Omega_d^A$), 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 :

$$r_{US}(t) = \left\{ [r_{in} + u_A \cos(\omega_{US}t + \delta) - u_D \cos(\omega_{US}t)]^2 \cos^2 \varphi + [u_A \cos(\omega_{US}t + \delta) - u_D \cos(\omega_{US}t)]^2 \sin^2 \varphi \right\}^{0.5}, \quad (14)$$

where ω_{US} 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 $\varepsilon_\sigma = [\sigma_{US} - \sigma(r_{in})]/\sigma(r_{in})$ and coupling parameters $\varepsilon_{RDA} = [R_{DA,US} - R_{DA}(r_{in})]/R_{DA}(r_{in})$, where σ_{US} and $R_{DA,US}$ are averaged over the AW period T_{US} :

$$\sigma_{US} = \frac{1}{T_{US}} \int_0^{T_{US}} \sigma(r_{US}(t)) dt, \quad R_{DA,US} = \frac{1}{T_{US}} \int_0^{T_{US}} R_{DA}(r_{US}(t)) dt.$$

In this estimation, the relaxation time in the CDLR subsystem is assumed to be considerably less than T_{US} and the previously used⁴¹ 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 $(\Delta\Omega_d^D \cdot \Delta\Omega_d^A) > 0$, or to 180° , if $(\Delta\Omega_d^D \cdot \Delta\Omega_d^A) < 0$. In addition, ε_{RDA} dependence on u_D and u_A is only determined by $|u_D - u_A|$ ($\delta = 0^\circ$ case) or $|u_D + u_A|$ ($\delta = 180^\circ$ 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 :

$$\varepsilon_\sigma = (u_D \pm u_A)^2 / 2 r_{in}^2 = K_{US}^{DA} W_{US}, \quad (15)$$

where “+” and “−” correspond to $\delta = 180^\circ$ and $\delta = 0^\circ$ respectively, K_{US}^{DA} characterizes defect couple–ultrasound

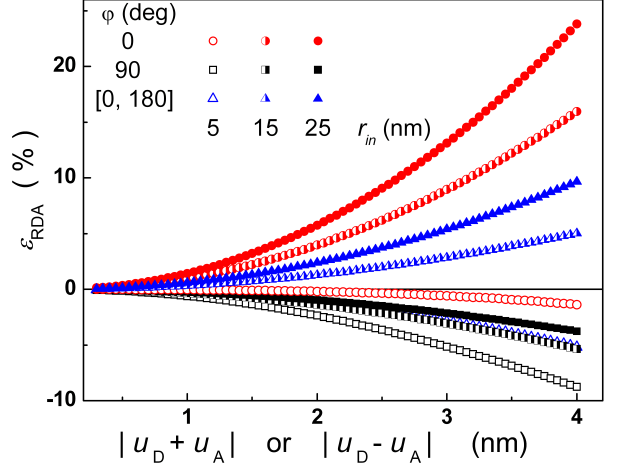


FIG. 6. Simulated dependencies of AI changes of coupling parameter on the vibration amplitudes. Axis $|u_D - u_A|$ corresponds to $\delta = 0^\circ$ case, whereas axis $|u_D + u_A|$ corresponds to $\delta = 180^\circ$ case. The parameters are set to $a_0 = 3.23$ nm, $r_{in} = 5$ nm (open marks), 15 nm (semi-filled marks), and 25 nm (filled marks), $\varphi = 0^\circ$ (circles), 90° (squares). Triangles correspond to mean ε_{RDA} value for $[0^\circ \div 180^\circ]$ φ range.

interaction and depends on properties defects as well as crystal matrix. It is taken into account in Eq. (15), that $u_D, u_A \propto \xi_{US} \propto \sqrt{W_{US}}$.

It is worth keeping in mind, that CLDR current flows locally in the locations of extended defects.^{41,58} 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 III C). 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 $(\Delta\Omega_d^D \cdot \Delta\Omega_d^A > 0)$ should be predominantly parallel to dislocation line, whereas the axis of the pair of coupled defects with $(\Delta\Omega_d^D \cdot \Delta\Omega_d^A < 0)$ 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:

$\delta = 0^\circ, \varphi = 90^\circ$ ($\Delta\Omega_d^D \cdot \Delta\Omega_d^A > 0$ case);

$\delta = 180^\circ, \varphi \in [0^\circ \div 180^\circ]$ ($\Delta\Omega_d^D \cdot \Delta\Omega_d^A < 0$ case).

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 $\Delta\Omega_d^D \cdot \Delta\Omega_d^A > 0$ case.

Taking into account the experimental results and suggested model estimation:

(i) $E_{\tau g}$ and T_{id} are mainly determined by couple component energy levels. The alteration of $E_{\tau g}$ 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 re-

sults in ε_σ and ε_{RDA} , which increase with W_{US} .
 (iii) Acoustically induced E_{τ_g} (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 conformationally bistable (or metastable) and transforms from ground state to another under US action. Similar AI defect variations were also reported previously.^{3,5,32,59}
 (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 Δn_{id} and ε_{τ_g} sign change is an evidence of transformation from $(\Delta\Omega_d^{\text{D}} \cdot \Delta\Omega_d^{\text{A}} > 0)$ to $(\Delta\Omega_d^{\text{D}} \cdot \Delta\Omega_d^{\text{A}} < 0)$ after irradiation. Transformation is confirmed by rise of US influence efficiency in irradiated samples. Really, in the case of $(\Delta\Omega_d^{\text{D}} \cdot \Delta\Omega_d^{\text{A}} < 0)$ 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 III D.

B. Quasi-neutral region

Base lifetime mirrors the processes, which occur in the quasi-neutral region of p - n -structure. Fig. 7 shows the τ_n behaviour in the explored temperature range. Minority carrier lifetime expectedly rises with temperature increase and τ_n values equal to $2 \div 5 \mu\text{s}$ for different samples at 320 K. These values correspond to $80 \div 130 \mu\text{m}$ range of diffusion length. In our opinion, the observed τ_n dispersion is not defined by irradiation, but deals with sample-ancestor wafer inhomogeneity, which is revealed quite often.^{60,61}

Really, the irradiation induced lifetime reduction is described by the Messenger-Spratt equation:⁴⁸

$$\tau_n^{-1} = \tau_{n0}^{-1} + K_\tau \Psi, \quad (16)$$

where τ_{n0} is the minority carrier lifetime in the non-irradiated sample, and K_τ is a lifetime damage-constants. The known K_τ values and estimated changes of reciprocal base lifetime $K_\tau \Psi$ are shown in the Table V. It shows, that the estimated value of radiation-induced τ_n^{-1} change equals to $(8 \div 17)$, 4, and 29 % of its measured value for samples nSC, g6SC, and g7SC respectively, and cannot explain dispersion observed experimentally. Calculated lifetime changes $K_\tau \Psi$ are in quite good agreement with those, which are expected from RDs production — see Section III D.

Base lifetime can be expressed as following:⁶⁴

$$\tau_n^{-1} = \tau_{\text{bb}}^{-1} + \tau_{\text{CE Auger}}^{-1} + \tau_{\text{SRH}}^{-1}, \quad (17)$$

where τ_{bb} , $\tau_{\text{CE Auger}}$, τ_{SRH} are the lifetimes of band-to-band, Coloumb-enhanced Auger, and SRH recombination, respectively. Calculation shows, that $\tau_{\text{bb}}^{-1} = 14 \text{ s}^{-1}$, $\tau_{\text{CE Auger}}^{-1} = 6 \text{ s}^{-1}$ and can be neglected. In case of low

TABLE V. Measured and estimated base lifetime parameters.

Sample	$\tau_{n,\text{in}}^{-1}$ (320 K) (10^5 s^{-1})	K_τ (cm^2/s)	$K_\tau \times \Psi$ (10^4 s^{-1})	$K_{\text{US}}^{\text{eff}}$ (cm^2/W)
iSC	2.9	—	—	3.5
nSC	4.7	10^{-7} (Ref. 33) $2 \cdot 10^{-7}$ (Ref. 62)	$4 \div 8$	7.1
g6SC	1.8	$5 \cdot 10^{-12}$	0.8	6.0
g7SC	2.8	(Refs. 33, 63)	8	5.2

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

$$\tau_n^{-1} = \sum_i^{M_d} \tau_{n,i}^{-1} = \sum_i^{M_d} N_{d,i} \sigma_{n,i} v_{\text{th},n}, \quad (18)$$

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 $\sigma_{n,i}$ are the concentration and electron CCS of i -th defect, respectively.

Fig. 7 shows, that USL results in τ_n decrease. Relative AI changes of reciprocal base lifetime $\varepsilon_{\tau n} = (\tau_{n,\text{in}} - \tau_{n,\text{US}})/\tau_{n,\text{US}}$ 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 III A, 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_d^{AA} and M_d^{nonAA} are the total numbers of acoustically active (AA) and non-AA center, Eq (18) for τ_n^{-1} under USL and without it takes the following shape

$$\begin{aligned} \tau_{n,\text{in}}^{-1} &= \sum_j^{M_d^{\text{AA}}} N_{d,j} \sigma_{n,j}^{\text{in}} v_{\text{th},n} + \sum_l^{M_d^{\text{nonAA}}} N_{d,l} \sigma_{n,l} v_{\text{th},n}, \\ \tau_{n,\text{US}}^{-1} &= \sum_j^{M_d^{\text{AA}}} N_{d,j} \sigma_{n,j}^{\text{US}} v_{\text{th},n} + \sum_l^{M_d^{\text{nonAA}}} N_{d,l} \sigma_{n,l} v_{\text{th},n}. \end{aligned}$$

Using Eq (15), $\varepsilon_{\tau n}$ transforms as follows

$$\varepsilon_{\tau n} = K_{\text{US}}^{\text{eff}} W_{\text{US}}, \quad (19)$$

where $K_{\text{US}}^{\text{eff}}$ characterizes ADI in the sample and depends on concentration of both AA and non-AA centers

$$K_{\text{US}}^{\text{eff}} = \sum_j^{M_d^{\text{AA}}} \frac{\tau_{n,\text{in}}}{\tau_{n,j,\text{in}}} K_{\text{US},j}, \quad (20)$$

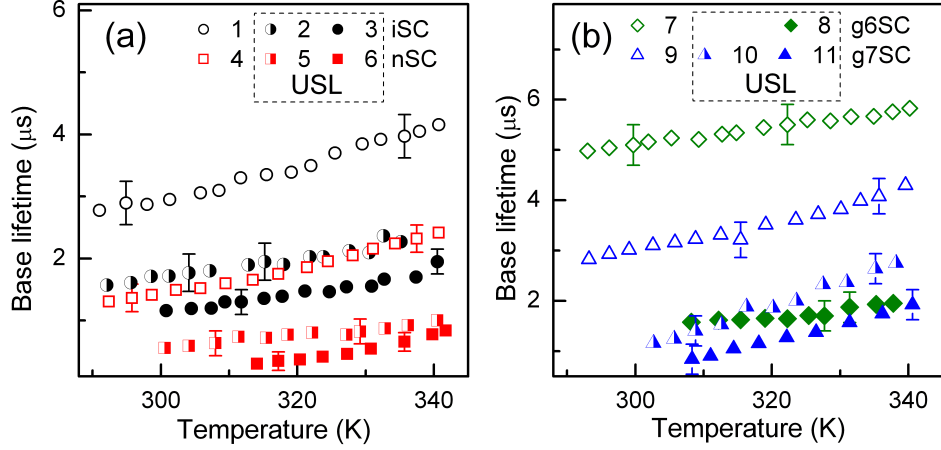


FIG. 7. Temperature dependences of base lifetime for non-irradiated (curves 1–3, circles), neutron-irradiated (4–6, squares) and γ -irradiated (7–11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui-1, Ui-2,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

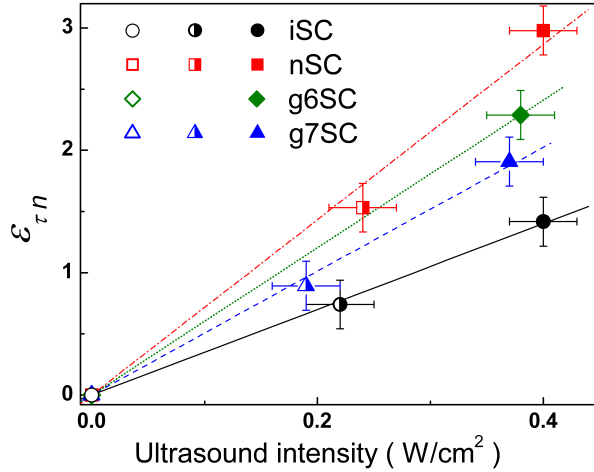


FIG. 8. Dependences of base lifetime relative change on US intensity for non-irradiated (circles), neutron-irradiated (squares), and γ -irradiated (triangles and diamonds) samples. Lines are the fitted curves using Eq. (19).

$K_{US,j}$ deals with j -th defect-ultrasound interaction.

The obtained dependences $\varepsilon_{\tau n}$ vs W_{US} are shown in Fig. 8. Linearity of these dependencies prove correctness of our assumptions. The determined K_{US}^{eff} values are listed in the Table V. The non-monotonic K_{US}^{eff} alteration with γ dose is discussed in Section III D.

C. 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 temper-

ature 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.⁶⁶ They are aluminum particles, macroscopic Si_3N_4 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 Si_3N_4 inclusions occur in multicrystalline silicon cells mainly⁶⁶ 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.^{66–68} In our opinion, both aluminum particles and dislocations are present in the investigated structure. The overall shunt resistance can be expressed as

$$R_{sh}^{-1} = R_{sh,A1}^{-1} + R_{sh,dis}^{-1}, \quad (21)$$

where $R_{sh,A1}$ and $R_{sh,dis}$ deal with aluminum particles and dislocations, respectively. The linear temperature dependence of metal particles $R_{sh,A1}$ is suggested:

$$R_{sh,A1} = R_{293,A1}[1 + \alpha(T - 293)], \quad (22)$$

where $R_{293,A1}$ is the shunt resistance at 293 K and α is the resistance temperature coefficient.

Gopal and Gupta^{42,43} introduced the model of dislocation-induced impedance of photovoltaic detector. According to this model, the $R_{sh,dis}$ can be given by

$$R_{sh,dis} = \frac{T}{\sigma_{dis}} \left[\cosh \left(\frac{E_{dis} - E_i}{kT} \right) + \cosh \left(\frac{U_s}{kT} \right) \right], \quad (23)$$

with

$$\sigma_{dis} = \rho_{dis} A q^2 A_{dis} \sqrt{K_n K_p} N_{dis} (n_p + p_p) / k, \quad (24)$$

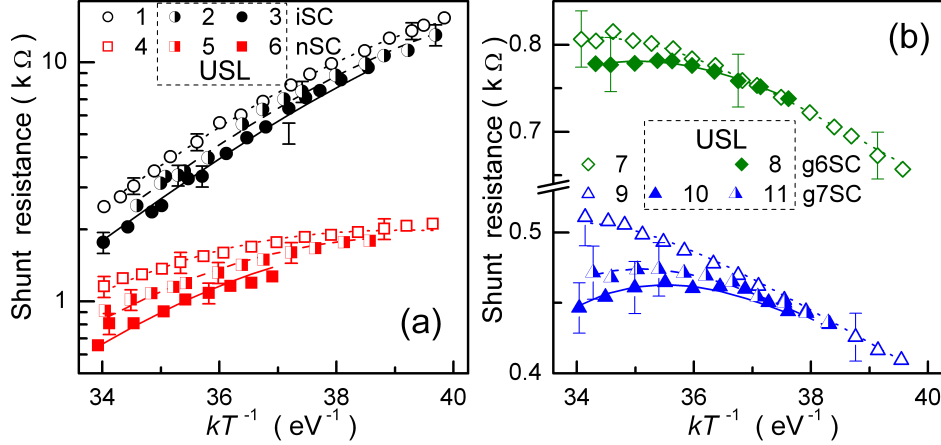


FIG. 9. Temperature dependences of shunt resistance for non-irradiated (curves 1–3, circles), neutron-irradiated (4–6, squares) and γ -irradiated (7–11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui-1, 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).

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 $8.3 \cdot 10^{-3} \text{ K}^{-1}$ is not far from resistance temperature coefficient of bulk Al ($4.3 \cdot 10^{-3} \text{ K}^{-1}$). Then we used Eqs. (21)–(23) to fit the experimental R_{sh} data. $R_{293, \text{Al}}$, $(E_{\text{dis}} - E_i)$, 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 $(E_{\text{dis}} - E_i) = (0.46 \pm 0.02) \text{ eV}$ and $U_s = (5 \pm 4) \times 10^{-8} \text{ eV}$, which were independent of irradiation and USL. The obtained value of $(E_{\text{dis}} - E_i)$ corresponds to the carrier activation energy $0.10 \pm 0.02 \text{ eV}$. This value is comparable to the activation energy of dislocation levels 0.08 eV , which was early reported^{69–73} in Cz-Si:B too.^{69–71}

Obtained values of $R_{293, \text{Al}}$ and σ_{dis} are listed in the Table III. $R_{293, \text{Al}}$ does not depend on USL and increases with irradiation level. In our opinion, $R_{sh, \text{dis}}$ is less than $R_{sh, \text{Al}}$ in iSC. Irradiation leads to vacancy production and Al diffusion out of electrodes. As a result, the quantity of Al particles rises, $R_{sh, \text{Al}}$ 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 τ_n correlate on samples set. Hence it deals with wafer inhomogeneity too. USL leads to σ_{dis} increase, relative AI changes $\varepsilon_{\sigma_{\text{dis}}} = (\sigma_{\text{dis, US}} - \sigma_{\text{dis, in}}) / \sigma_{\text{dis, in}}$ are shown in the Table IV. In our opinion this is caused by an A_{dis} augmentation. Namely, the dis-

location 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 $LR_{sh, \text{dis}}$ decreases under US action.

D. Defect type speculation

Lifetime killers in boron-doped Czochralski-grown Si are the boron-oxygen related (BO) defects,^{74,75} iron-boron pairs^{64,76,77} (or another Fe-related trap in the n^+p -junctions^{78,79}), and oxide precipitates.^{60,61,64,80–82} 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^{74,75} 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

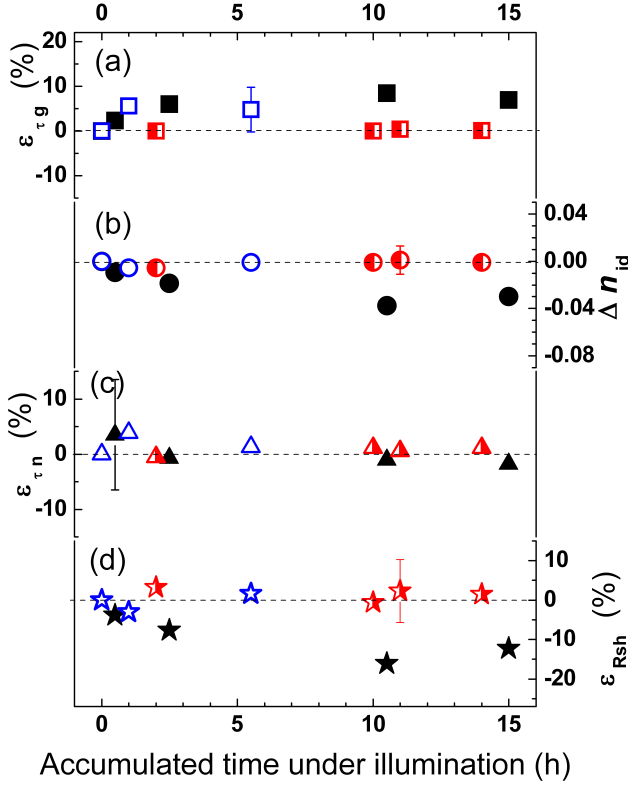


FIG. 10. Permanent changes of SCR lifetime (a, squares), ideality factor (b, circles), base lifetime (c, triangles), and shunt resistance (d, asterisks) versus accumulated illumination time. Sample iSC, $T = 295$ K. Filled, semi-filled and open marks correspond to sample before annealing, after first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

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 τ_g , τ_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. Fe_iB_s can be readily dissociated under intense illumination to release interstitial iron. This gives a lifetime change. In dark Fe_iB_s repairing takes place and Fe_i concentration decreases according to^{64,83}

$$N_{Fe}(t) = (N_{Fe,0} - N_{Fe,eq}) \exp\left[-\frac{t}{\tau_{rep}}\right] + N_{Fe,eq}, \quad (25)$$

where $N_{Fe,0}$ and $N_{Fe,eq}$ are the concentration after illumination immediately and equilibrium concentration which remains a long time after dissociation respectively, and the characteristic time of repairing τ_{rep} depends on doping level

$$\tau_{rep} = 770 \cdot p_p^{-2/3} \exp\left(\frac{E_{D,Fe}}{kT}\right), \quad (26)$$

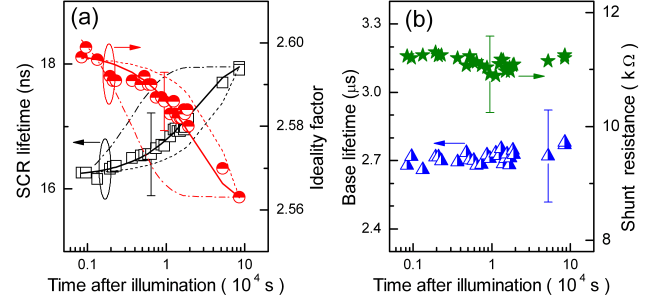


FIG. 11. SCR lifetime (a, squares, left axis), ideality factor (a, circles, right axis), base lifetime (b, triangles, left axis), and shunt resistance (b, asterisks, right axis) as a function of time since illumination stopping. Sample iSC, $T = 295$ K. Lines are calculated by using Eqs.(25)–(26) and $E_{D,Fe} = 0.63$ eV (dash-dotted lines), 0.68 eV (solid lines), and 0.73 eV (dashed lines).

$E_{D,Fe} = 0.68$ eV is the activation energy of Fe_i diffusion. n_{id} increase (about 0.03) and τ_g decrease (about 10 %) immediately after illumination were observed — see Fig. 11(a). These changes vanished gradually. We supposed that the τ_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. 11(a). The fittings with $E_{D,Fe} = 0.68$ 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 Fe_i are 1.7 and 0.04 times⁶⁴ as much as those of Fe_iB_s . A small (about 10 %) τ_g alteration, which is caused by light, is evidence of supporting role of iron-boron pair in SCR recombination. Furthermore, since τ_n does not depend on illumination (see Fig. 11(b)), then Fe_iB_s does not influence on base lifetime.

As a result, oxide precipitates are number one in SCR and base recombination. According to Murphy *et al.*^{80,81}, at least two independent oxide precipitate related defects exist. These defects have $\sigma_n/\sigma_p = 157$ and $\sigma_p/\sigma_n = 1200$ respectively.⁸¹ 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, $\sim 7 \cdot 10^{17} \text{ cm}^{-3}$, p -Si with boron concentration $\sim 10^{15} \text{ cm}^{-3}$ and low dose) it is expected, that C_iO_i , vacancy clusters V_n (divacancy V_2 , trivacancy V_3 , ...) and VO_i are produced mainly by neutron irradiation^{84–86} and C_iO_i and VO_i by γ -rays.^{86–89} The RD concentration $N_{t,RD}$ 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 $N_{t,RD}$ 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

TABLE VI. Cited and calculated defect parameters.

Defect	σ_n	η_n (cm ⁻¹)	η_γ	$N_{t,rd}(10^{11} \text{ cm}^{-3})$			$\tau_{n,rd}^{-1} (10^4 \text{ s}^{-1})$		
	(10 ⁻¹⁵ cm ²)	Ref. 86		nSC	g6SC	g7SC	nSC	g6SC	g7SC
C _i O _i	0.7 (Ref. 87) 0.9 (Ref. 88)	1.38	6·10 ⁵ rad ⁻¹ cm ⁻³ (Ref. 87) 4·10 ⁻⁴ cm ⁻¹ (Ref. 88)	5.5	6	60	0.8 ÷ 1	0.9 ÷ 1.1	9 ÷ 11
V ₂	3 (Ref. 87) 2 (Ref. 90)	1.21	3·10 ⁴ rad ⁻¹ cm ⁻³ (Ref. 87)	4.8	0.3	3	2.2 ÷ 3.3	0.1 ÷ 0.2	1 ÷ 2
V ₃	2.4 (Ref. 91)	0.37	—	1.5	—	—	0.7	—	—
VO _i	2.4 (Ref. 89) 4 (Ref. 92)	0.52	7·10 ⁵ rad ⁻¹ cm ⁻³ (Ref. 87) 4·10 ⁻⁴ cm ⁻¹ (Ref. 88)	2	6 ÷ 7	60 ÷ 70			

introduction rate. For example, expected^{85,93} concentration of BD is only $(1 \div 2) \cdot 10^{10} \text{ cm}^{-3}$ in nSC and g7SC. The lack of B_iO_i in investigated samples deals with low boron concentration⁹⁴. Lastly, C_iC_s creation is suppressed in oxygen-rich crystal.^{84,87,88} Besides C_iC_s is not recombination active center.⁹⁵

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.^{63,96–99} Estimated $\tau_{n,rd}$ for C_iO_i, V₂, and V₃ are shown in Table VI. It shows that τ_n is effected mainly by C_iO_i and vacancy clusters in γ - and neutron-irradiated samples, respectively. It should be noted, that nSC, g6SC, g7SC sums of $\tau_{n,rd}$ are in quite good agreement with $(K_\tau \cdot \Psi)$ values.

Lets consider K_{us}^{eff} assuming that $M_d^{AA} = 1$, $M_d^{nonAA} = 1$ in non-irradiated sample and US interaction with C_iO_i and V_n is described by K_{us}^{CO} and K_{us}^V , respectively. Then Eq. (20) gives the following expression for K_{us}^{eff} in nSC and irradiated samples:

$$K_{us}^{eff} = K_{us}^{AA} \tau_{n,in} / \tau_{n,in}^{AA},$$

$$K_{us}^{eff} = K_{us}^{AA} \tau_{n,in} / \tau_{n,in}^{AA} + K_{us}^{CO} \tau_{n,in} / \tau_{n,rd}^{CO} + K_{us}^V \tau_{n,in} / \tau_{n,rd}^V.$$

$\tau_{n,in}^{AA}$ is the base lifetime of the sample, where non-radiative AA defect with K_{us}^{AA} 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 $(\tau_{n,in}^{-1} - K_\tau \cdot \Psi)$ values in different samples. In the second one, a non-AA defect distribution is not uniform, whereas $\tau_{n,in}^{AA}$ is identical for iSC, nSC, g6SC, and g7SC. However, in the first case (as well as in case of $M_d^{nonAA} = 0$), experimental K_{us}^{eff} values lead to unreal (negative) values of $K_{us,j}$. In the second case, Eq. (20) and the data from the Tables V and VI, give the following array equations:

$$\begin{aligned} \text{iSC} : 3.5 &= K_{us}^{AA} \cdot (\tau_{n,in}^{AA})^{-1} / 2.9, \\ \text{nSC} : 7.1 &= K_{us}^{AA} \cdot (\tau_{n,in}^{AA})^{-1} / 4.7 + 0.09 K_{us}^V + 0.02 K_{us}^{CO}, \\ \text{g6SC} : 6.0 &= K_{us}^{AA} \cdot (\tau_{n,in}^{AA})^{-1} / 1.8 + 0.01 K_{us}^V + 0.05 K_{us}^{CO}, \\ \text{g7SC} : 5.2 &= K_{us}^{AA} \cdot (\tau_{n,in}^{AA})^{-1} / 2.8 + 0.05 K_{us}^V + 0.35 K_{us}^{CO}, \end{aligned}$$

where $(\tau_{n,in}^{AA})^{-1}$ in 10⁴/s. These equations are correct if $K_{us}^{AA} \cdot (\tau_{n,in}^{AA})^{-1} = (10 \pm 3) \text{ cm}^2/\text{W}$, $K_{us}^V = (42 \pm 15) \text{ cm}^2/\text{W}$,

$K_{us}^{CO} = 0$. Since $(\tau_{n,in}^{AA})^{-1} < 1.83$, then $K_{us}^{AA} > 5 \text{ cm}^2/\text{W}$. 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 γ -irradiated samples. This effect is added by AI divacancy alteration in neutron-irradiated samples. In other words, C_iO_i is non-AA defect, whereas V₂ is AA defect.

As to SCR recombination, in our judgement, τ_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 III A, the AA radiation defects with $\Delta\Omega_d < 0$ take part in CDLR in irradiated samples. Divacancy is quite suitable explanation for AI influence on τ_g and n_{id} in nSC. But in γ -irradiated samples a bistable (or metastable) defect is expected. Few such defects with $\Delta\Omega_d < 0$ are known in Si, viz VO₂,¹⁰⁰ V₃,⁹¹ and VO_i.¹⁰¹ VO₂ appears after 300°C annealing of irradiated crystal, V₃ 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.¹⁰¹ The volume change of entire complex is negative, whereas for the complex component $\Delta\Omega_d(V) < 0$ and $\Delta\Omega_d(O_i) > 0$. 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 $E_{\tau g}$ change.

IV. 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 ef-

fects. 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.

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