10.1109/ULTSYM.2000.922602

ULTRASONIC INFLUENCE ON POINT DEFECTS IN A DISLOCATION FREE Si

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Abstract – Ultrasound (US) influence on dislocation free (DF) silicon is investigated. Ultrasonic waves attenuation (α), mobility of intentionally induced superficial dislocations, and minority carriers diffusion length (L) are measured from a dislocation free Cz-Si as a function of US amplitude. The general results consist of some changes in the properties under study that takes place in a threshold way. Under US deformation $S > 10^{-5}$ attenuation α becomes nonlinear, dislocation mobility and so microplasticity vary significantly, and L increases up to 2 times.

US in DF Cz-Si can effectively interact with a system of point defects. The acoustostimulated changes in DF Cz-Si properties under study are connected to ultrasonically activated transformations in a system of crystal point defects and their complexes.. We find there are two thresholds of US deformation: $S_1 \sim 10^{-6}$ and $S_2 \sim 10^{-5}$. Under deformation $S<S_1$ the defect system rests unchanged, at $S_1<S<S_2$ recombination properties and electrical activity of defects are modified, and under deformations $S>S_2$ the process of defects redistribution takes place.

I. INTRODUCTION

The main results on US interaction with crystal defects are accomplished for dislocation materials [1]. The linear defects can transform a portion of US energy to crystal lattice and change crystal properties. In case of a DF material there is no interaction through long range elastic fields, and so a fact of US action on a solid is not evident. It is a first question to be answered in the present work.

A progress is also achieved in experimental research on polycrystalline silicon [2], where US was applied to hydrogenated Si-based thin films, and it was shown that US could raise some additional hydrogen passivation of residual grain boundary defects. Note that these defects also possess long range elastic fields, and so the physical mechanism can be close to dislocation material case.

Another group of publications is devoted to US stimulation of the impurities diffusion [3]. Physical mechanism here is connected to the changes in population of vibration energetic levels. That leads to enhance a quantum diffusion of impurity species through crystal lattice. One can suppose exactly this effect could be responsible for US influence on DF crystal, but according to theoretical calculation [3] a significant enhancement of impurity diffusion could be expected at very low temperatures of 5 to 10 K.

Nowadays as experimental investigations, as theoretical calculations are still lacking for widely used DF crystalline silicon.

Surprisingly, our first experiments demonstrate a strong effect of US on DF Cz-Si. The purpose of this work is investigation of US influence on DF material.

II. SAMPLES AND EXPERIMENTAL TECHNIQUE

We use three types of DF Cz silicon samples: 1)IC grade bulk p-Si having specific resistance $\rho = 7.5$ kOhm cm (ICB samples), 2) IC grade wafers p-Si of $\rho = 9$ Ohm cm (ICW samples), and 3) Solar grade wafers p-Si of $\rho = 0.5–2$ Ohm cm (SGW samples). ICB samples are the bars of 5x5x10 mm^3, ICW – plates of 5x0.45x25 mm^3. SGW samples are plates of 5x0.34x25 mm^3 with oxygen concentration $N_O \leq 10^{18} cm^{-3}$, carbon concentration $N_C \leq 10^{17}$ cm^{-3}.

PZT transducers for longitudinal vibrations glued to the Si samples excite US in the range 0.3–6 MHz. US propagates along [100] direction in ICB samples, and in [111] plane for wafer type samples. Ultrasonic attenuation is measured in a resonance mode. Experimental procedure for dislocation mobility measurements consists of introducing of the superficial dislocations into our samples that were initially dislocation free, and following mechanical initiation of dislocations displacements.

Minority charge carriers diffusion length L is determined by a surface photovoltage method by measuring a spectral dependence of a surface photovoltage. In the case of SGW samples the US frequencies are f_1 = 0.8 MHz, f_2 = 1.8 MHz and f_3 = 5.4 MHz.

III. RESULTS AND DISCUSSIONS

Attenuation

Typical dependencies of ultrasonic attenuation on US deformation taken from our samples are presented on fig.1. Under respectively small US deformations ($S<10^{-7}$) attenuation α is not changed, but at S higher a threshold value that is about $S > 10^{-6}$ the attenuation

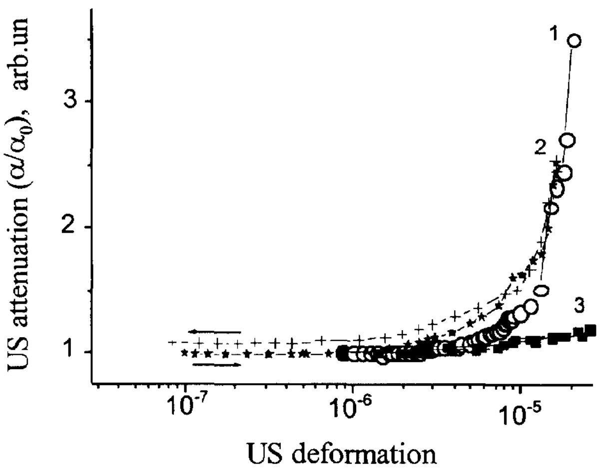

Fig.1. Attenuation on US deformation: 1 sample ICB-5N, 430 KHz, T=60 °C, α_0=2.6 dB/cm ; 2-ICW-RF4, 600 KHz, α_0=3dB/cm, T=30 °C; 3-Fuzed quartz, T=30 °C, 435 KHz.

increases and reaches a value 3-4 times higher of its initial value. Also a hysteresis is observed, as it is shown for plot 2 by two flashes representing different attenuation for beginning and finishing of one cycle of loading sample by US and following release. Under US deformations $S>10^{-5}$ a sample temperature increases up to 20 °C higher initial one. Note the amplitude dependencies of fig.1 can not be explained by any of existing theories for US attenuation [1,3,4].

We also measured US attenuation due to temperature increase only and found that temperature effects were much lower than ultrasonically induced α enhancement. Because our samples are DF type we can assume that the point defects can be responsible for US attenuation augment. Point defects in tour can be revealed by their influence on microplasticity and through the micrographes of samples etching.

Debris layer formation

On fig.2 we present the typical results for ICB.

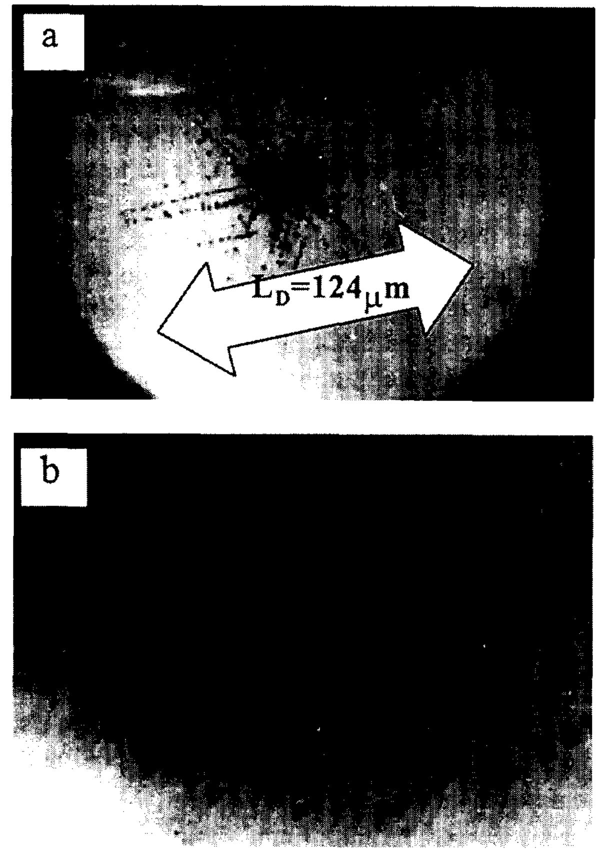

Fig.2. Micrographes of Cz-p-Si (ρ=7.5 kOhm cm) wafers before UST (a) and after UST (b), and following chemical etching: a–initial sample ISB-S1, L_D=124 mcm; b–sample ICB-S2, UST=30 min, f=450KHz, L_D=99 mcm.

A length of dislocation rose beams on fig.2-b decrease after ultrasonic treatment (UST). Length of beams characterizes a mobility of dislocations. The mobility of dislocations is reduced, which means a sample surface becomes harder due to UST. Also on sample surface there are the pits of the round and oval shapes (fig.2-b). They usually are connected to the presence of the point defects and their complexes at crystal surface. We estimate a thickness of a hardened layer by method of level-by-level polishing and chemical etching, this thickness is about 100 microns. At this depth from the surface the pits disappeared. Besides lengths of dislocation rose beams L_D increase. Thus after UST L_D is 40–60 mcm, but at depth 100 microns it becomes about 100–120 microns, i.e. typical initial value for the samples without UST.

The velocities (V) of intentionally induced dislocations in a near surface region are measured from ICW type samples – fig.3.

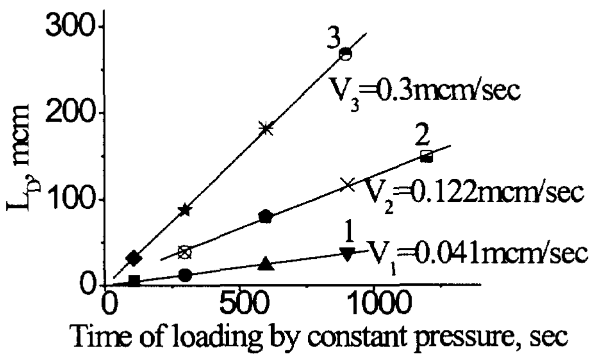

Fig.3. Dislocation displacement lengths L_D on time of loading for initial sample before UST (2), and after UST for stretching (3) and compressing (1).

The data on fig. 3 are taken from 12 samples of IC Si-wafers, they are represented by different points. Measurements are made at T = 600 °C, external pressure is 80 MPa (8 kg/mm^2 under load 700g). An inequality $V_1<V_2<V_3$ takes place at all temperatures of experiment T=550 to 650 °C.

Dislocation velocity is a function of activation energy E_d, acting strain τ, and heat energy (kT):

$$v = v_0 \frac{\tau b^3}{kT} exp\left(-\frac{E_d}{kT}\right), \quad (1)$$

where b- Burgers vector, v_0 – some constant.

Taking into consideration experimental results and formula (1) one can conclude that UST produce changes in E_d and τ. Temperature dependencies $V_d(T)$ taken from the samples under three different conditions marked as 1, 2 and 3 on fig.3 reveal two different activation energies: $E_{d1}=E_{d3}=1.62$ eV, and $E_{d2}=2.02$ eV.

Diffusion length of minority charge carriers

Diffusion length (L) is measured without US loading (L_0) and under US action (L). The initial L_0 are 15 to 25 mcm for different samples. Under US action L increases up to 2 times. The acoustostimulated change in L is reversible, and L returns to its initial value L_0 after UST. Typical kinetics of L(t) under constant US is shown on fig.4.

A maximum L value under UST (L_m) depends on

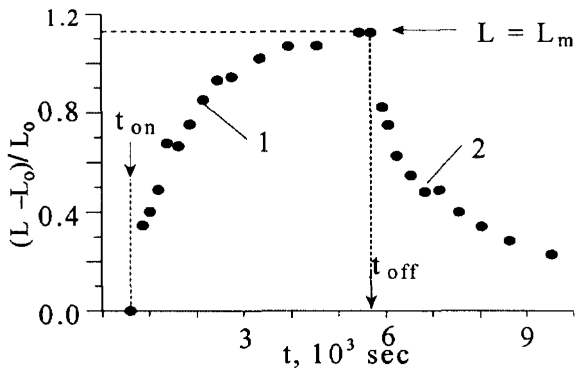

Fig.4. Dependence L on time after US is switched on (1) and off (2). f=0.8 MHz, rf-voltage to PZT=35V.

US amplitude. Representative dependence of L_m on US intensity is given on fig.5. The data of fig.5 are obtained from different samples and US frequencies, which are shown by different experimental points. One can see the dependence $L_m(W_{US})$ posses a certain threshold US intensity $W_{us}\sim 0.5$W/cm^2 (or S~4x10^{-6}), and a saturation is observed at $W_{US}>2.5$ W/cm^2 (or S > 0.8x10^{-5}. Note also a hysteresis character of dependence on fig.5 when cycling US loading. Increasing US amplitude during first applying of UST gives ABCD plot and subsequent decreasing – DEFA plot. Next cycles of sample loading go along AFED plot on fig.5.

The initial curve ABCD can be observed only after respectively long (2-3 weeks) storage of sample at room temperature without US action.

Physical mechanism

The physical mechanism of US influence on DF crystal can be associated with a subsystem of point defects including their different complexes

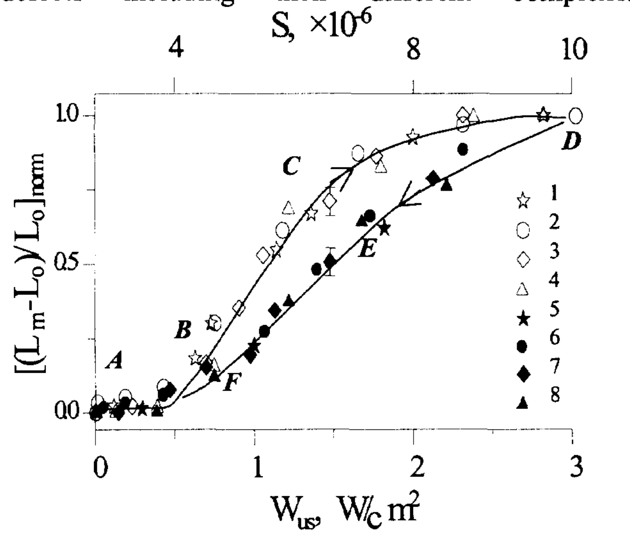

Fig.5. Dependency L_m on US intensity W_{US}. ABCD – 1-st cycle of W_{US} increase, DEFA – 1-st cycle of W_{US} decrease. 1, 5 – sample SGW-C1, f=0.78 MHz; 2,6 – C2, f=0.78 MHz, 3, 7 – C2, f=1.8 MHz; 4, 8 – C3, f=0.78 MHz.

(precipitates, vacancy containing structures, pairs of electrically charged defects, etc.). This approach is supported by the above experimental results: 1)nonlinear and threshold features of US attenuation (fig.1), 2) debris layer formation (fig.2), 3) direct evidence of increasing concentration of point defects in a near surface region after UST (fig.2-b), 4)change of dislocation velocity (fig.3), 5) characteristic times of the kinetics of minority charge carriers diffusion length under UST (fig.4), 6) character of amplitude dependence $L_m(W_{US})$ on fig.5.

In the case of superficial dislocations their mobility is controlled by energy E_d and strain τ. Because these parameters depends on UST, but US does not generate any new dislocations, a redistribution of point defects with their accumulation in a near surface region can explain all the observed results.

Diffusion length L in Si of average doping level ($<10^{18}$ cm^{-3}) at room temperature is determined by recombination through the deep traps [5]. According to the Shockley-Read-Hall model:

$$L^{-2} = D^{-1} V_T \sum \sigma_i N_i \qquad (2)$$

Where D and V_T – are electron diffusion coefficient and thermal velocity, σ_i and N_i are cross section and concentration of recombination centers, respectively. In Cz-Si length L is controled by heavy metal impurities, and Fe is a very effective impurity to decrease L [5]. Fe ions in boron-doped p-Si ($N_B>10^{15}$ cm^{-3}) at room temperature tend to form the bistable pairs Fe_i-B_{Si} [6] with two close possible distances between Fe_i and B_{Si} (r_A=2.35A and r_B=2.72 A) but having different cross sections ($\sigma_A >> \sigma_B$). Last inequality is due to different concentrations of Fe_i^{2+} and Fe_i^{+} in A- and B-states. Under US action a transition from A- to B-state can be activated because of small alteration of potential barrier width and activation energy for this transition. After US turned off the system returns to its initial state (fig.4, plot2).

V. Conclusions

1. Interaction between US and point defects in DF Si is shown to be effective in MHz range. 2. For the first time stimulated by US increase of minority carriers diffusion length in SG Si is revealed. 3. The near surface hardened can be created by UST.

VI. References

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