

Dear editor,

We like to express our appreciation to the reviewers for their comments. We are re-submitting the revised version of the paper number JAP21-AR-DIS2022-05281. We have studied the comments of the reviewer carefully, and have changed the text according to the comments they have listed. The location of revisions is pointed by blue color in “Marked-Manuscript.pdf”. Below we refer to each of the reviewers comments.

### Response to Reviewer #1

**Comment 1.** *The English expression is a little awkward in places, but not to the extent that it negatively affects the readability, in my opinion.*

**Reply:** The text was revised.

### Response to Reviewer #2

**Comment 1.** *In Fig. 4, the numbers identifying the different curves are missing.*

**Reply:** The curves’ numbers were added. We apologize for the inattention.

**Comment 2.** *Figure 6 is not so relevant, and could be given as supplementary information*

**Reply:** Figure 6 was transferred to the Supplementary material, the text was revised (page 5, column 1, paragraph 2).

### Response to Reviewer #3

**Comment 1.** *Page 1, column 2, line 1: The lattice deformation amplitude should have a unit.*

**Reply:** The “relative deformation” was meant. The term “strain” is used in the revised version.

**Comment 2.** *Page 1, column 2, paragraph 3: The origin of the iron in the diodes should be explained. How are the diodes contaminated with iron?*

**Reply:** The technological process of solar cells (SCs) manufacturing from Cz-p-Si wafers included the formation of separating and isotype barriers ( $n^+$ - $p$  and  $p$ - $p^+$  junctions) by diffusion of phosphorus ( $\text{POCl}_3$ ) and boron ( $\text{BCl}_3$ ) from the gas phase, respectively; thermal oxidation; thermal annealing; photolithography; etching the dividing groove; chemical treatments; magnetron sputtering of aluminum contacts to the front and back sides.

It was found that some SC lots have significantly worse parameters compared to typical solar cells for this process. In particular, the photoconversion efficiency was almost halved. The analysis showed that the reason for such a deterioration in the SC parameters is a sharp drop in the diffusion length of minority charge carriers (electrons)  $L_n$  in the SC base. Additional experiments with thermal annealing at temperatures of 200°C and 90°C (the procedure is described by Tayyib *et al.*<sup>1</sup>) showed that the decrease in  $L_n$  value is connected to the presence of an iron impurity with a concentration of up to  $4 \cdot 10^{13} \text{ cm}^{-3}$ . It was also found that the source of iron impurity is insufficiently pure chemicals that were used for chemical treatments in the technological process, obtained from another supplier. These reagents were the source of contamination in the process of manufacturing experimental SC samples.

To study the effect of ultrasonic loading on the kinetics of the transformation of iron-boron pairs, samples with varying degrees of iron contamination (iron concentration  $2 \cdot 10^{12}$ - $4 \cdot 10^{13} \text{ cm}^{-3}$ ) were taken.

More detailed information about iron sources was added (page 1, column 2, paragraphs 3 and 4).

**Comment 3.** *Page 1, column 2, paragraph 5: How was the excess carrier density, which is induced by the LED illumination, estimated? This point should be explained.*

**Reply:** The excess carrier density was estimated by using open-circuit voltage value  $V_{\text{OC}}$ . According to Sachenko *et. al.*<sup>2</sup>

$$\Delta n = -\frac{n_0}{2} + \sqrt{\frac{n_0^2}{4} + n_i \exp\left(\frac{qV_{\text{OC}}}{kT}\right)} \quad (1)$$

where  $n_0$  is the equilibrium electron concentration,  $n_i$  is the intrinsic electron concentration.

The short information was added to the revised manuscript (page 2, column 1, paragraph 3).

**Comment 4.** *Figure 2: Short circuit current has the unit  $\mu A$  not  $\mu m$ .*

**Reply:** The reviewer is quite right. The graph was corrected.

**Comment 5.** *Page 2, column 2, paragraph 1: The materials doping level is given on page 1 with 10 Ohm cm. This is about  $1.4e15cm^{-3}$  and not  $1.4e16cm^{-3}$  as stated here.*

**Reply:** The reviewer is quite right. It was a slip. The correction is done.

**Comment 6.** *Equation 7: The unit of the pre-factor is missing.*

**Reply:** The Equation was corrected.

**Comment 7.** *Page 3, column 1, paragraph 3: The obtained iron concentration is compared to results obtained from diffusion length measurements. There should be a reference to these measurements or more details should be given.*

**Reply:** The diffusion length before ( $L_{n0}$ ) and after ( $L_{n1}$ ) pair dissociation was measured using spectral dependencies of short circuit current<sup>3</sup>. Then the iron concentration was determined by using Zoth and Bergholz<sup>4</sup> equation:

$$N_{Fe}(cm^{-3}) = 1.06 \cdot 10^{16} \left( \frac{1}{L_{n1}^2} - \frac{1}{L_{n0}^2} \right) (\mu m^{-2}) \quad (2)$$

The short information was added to the revised manuscript.

**Comment 8.** *Figure 4: The numbers of the curves given in the caption are not included in the graphs. This must be improved otherwise the figures cannot be understood. Each graph should also be marked by a letter. What is “G” at the x-axis of the inset? This should be explained.*

**Reply:** The graphs were revised. The curves’ numbers were added. Each graph was marked by a letter. “G” was changed by “Will” (radiation intensity of halogen lamp). We apologize for the inattention.

**Comment 9.** *Figure 5: This plot is confusing and must be revised. What is the main statement of this figure? What are the differences between the samples and why do the*

results change from sample to sample? The axes should have the same scaling. What are the light blue bars in (a)?

**Reply:** Figure 5 was changed by Table I. The main assignment of this data is an illustration of

- i) USL actually does not influence the  $\tau_{\text{dis}}$  magnitude;
- ii) some pairs do not dissociate under illumination in the USL case when light-induced pair dissociation is close to saturation. The decrease in illumination intensity reduces the last effect at the given illumination times.

The main differences between the samples are the iron concentrations. However, data show that the effect of ultrasound does not qualitatively change with the iron concentration alteration (from sample to sample). The value of acousto-induced change in  $N_{\text{Fe,fit}}$  value depends on ultrasound intensity (see data for sample SC350-1,  $W_{\text{ill}} = 0.16 \text{ W/cm}^2$ ) and frequency.

The dissociation rate of FeB pairs depends on iron concentration, light intensity, and temperature<sup>5-8</sup>. There is a reason of  $\tau_{\text{dis}}$  value change from panel to panel in Fig. 5 in the unrevised manuscript (from row to row in Table I in the revised manuscript)

The light blue bars in Fig. 5(a) (the unrevised manuscript) corresponded to another ultrasound intensity ( $0.6 \text{ W/cm}^2$ ).

**Comment 10.** *Main Problem The impact of ultrasound on the iron-boron-pair reaction was first reported by Ostapenko and Bell in 1995 [1]. They found that the iron boron pairs dissociate due to an ultrasound treatment. This is in contradiction to the findings, which are reported herein. In the contribution under review it is found that the association of the FeB pairs is enhanced by the ultrasound treatment. This contradiction must absolutely be discussed by the authors otherwise the manuscript cannot be published.*

[1] S. S. Ostapenko and R. E. Bell, "Ultrasound stimulated dissociation of Fe-B pairs in silicon," *J. Appl. Phys.*, vol. 77, no. 10, p. 5458, 1995.

**Reply:** We do not keep silent about reports Ostapenko *et al.* — see Refs.26,27; page 3, column 2, paragraph 1; page 7, column 2, paragraph 1 in the unrevised manuscript. But Reviewer is right and more attention should be paid to the comparison of the findings.

In our opinion, the reported herein and previous results have a lot in common. According

to Ostapenko *et al.*<sup>9</sup>  $\text{Fe}_i$  has to “jump” to the next nearest interstitial under ultrasound action; we state about the decrease in  $\text{Fe}_i$  migration energy value as well as enhance of  $\text{Fe}_i$  diffusivity in the ultrasound loading case. The effectiveness of ultrasound influence increase with temperature rise in both cases: according to Ostapenko *et al.*,<sup>9,10</sup> the diffusion length increases from  $10.5 \mu\text{m}$  to  $13 \mu\text{m}$  at  $20^\circ\text{C}$  and up to  $22 \mu\text{m}$  at  $70^\circ\text{C}$ ;  $\Delta E_{\text{US}}$  increases from  $3 \text{ meV}$  to  $8 \text{ meV}$  with temperature change from  $300 \text{ K}$  to  $340 \text{ K}$  at  $f_{\text{US}} = 0.3 \text{ MHz}$  and  $W_{\text{US}} = 0.76 \text{ W/cm}^2$  (Fig.6 in the revised manuscript). The difference in the main results of the sound action (the iron-boron pairs dissociation or the enhancing of pairing) is associated with the difference in the intensity of the acoustic influence. The acoustic strain  $\xi_{\text{US}} = 10^{-5} - 10^{-4}$  was used<sup>11</sup> to dissociate FeB pair in Cz-Si. Furthermore, Ostapenko and Bell<sup>11</sup> regarded the resonance condition of pair reorientation (first step of dissociation) and used  $25 - 70 \text{ kHz}$ . In our case,  $\xi_{\text{US}} < 2 \cdot 10^{-6}$  and  $f_{\text{US}} = 2 - 30 \text{ MHz}$  are deficient to effectively overcome the Coulombic attraction between  $\text{Fe}_i^+$  and  $\text{B}_s^-$ . Additionally, the presented data show that the effectiveness of acoustically-induced change decreases as the ultrasound frequency increases.

It should be noted that Ostapenko *et al.*<sup>10</sup> asserted “in the case of predominant dissociated pairs, it [ultrasound treatment] may promote the pairing reaction” (page 1557, column 1, paragraph 2). In our case, the predominant dissociation has been realized by intense illumination, and then the ultrasound loading accelerated pairing. Thus, the reported results provided empirical evidence for the above-mentioned prediction.

On the other hand, a certain manifestation of partial acoustically-induced FeB dissociation could be a decrease in the concentration of pairs, which dissociate under illumination in the USL case. In fact, if some pairs were dissociated by ultrasound waves, which have been pre-exited in the sample with a high initial fraction of paired Fe, they can not be dissociated under illumination. The decrease in the temperature or photon quantity leads to reduce in the set of FeB, which was modified by ultrasound, or in the set of FeB, which was modified by the capture of light-induced electrons, respectively. Sets cease to overlap and  $N_{\text{Fe,fit}}(W_{\text{US}} > 0) \simeq N_{\text{Fe,fit}}(W_{\text{US}} = 0)$  — see Table I in the revised manuscript.

Finally, let’s summarize the differences between the manuscript and previously reported results. Ostapenko *et al.*<sup>9-11</sup> investigated the change in silicon properties (diffusion length) **after** the action of ultrasound with high (above threshold) intensity. This is the so-called ultrasound treatment mode of operation and results can be used to develop a new approach to

semiconductor properties modification. Our manuscript is devoted to the modification of the process (short circuit current kinetics or FeB transformation), **during** subthreshold acoustic wave propagation. This is ultrasound loading mode, which can be used for acoustically controlled tuning of the technological processes.

The additional information was added to the revised manuscript (page 7, column 1, last paragraph; page 7, column 2, paragraph 1).

## REFERENCES

- <sup>1</sup>M. Tayyib, J. Theobald, K. Peter, J. Odden, and T. Stre, Energy Procedia **27**, 21 (2012), proceedings of the 2nd International Conference on Crystalline Silicon Photovoltaics SiliconPV 2012.
- <sup>2</sup>A. V. Sachenko, Y. V. Kryuchenko, V. P. Kostylyov, A. V. Bobyl, E. I. Terukov, S. N. Abolmasov, A. S. Abramov, D. A. Andronikov, M. Z. Shvarts, I. O. Sokolovskyi, and M. Evstigneev, J. Appl. Phys. **119**, 225702 (2016).
- <sup>3</sup>E. D. Stokes and T. L. Chu, Appl. Phys. Lett. **30**, 425 (1977).
- <sup>4</sup>G. Zoth and W. Bergholz, J. Appl. Phys. **67**, 6764 (1990).
- <sup>5</sup>J. Schmidt, K. Bothe, V. V. Voronkov, and R. Falster, physica status solidi (b) **257**, 1900167 (2020).
- <sup>6</sup>L. J. Geerligs and D. Macdonald, Appl. Phys. Lett. **85**, 5227 (2004).
- <sup>7</sup>N. Khelifati, H. S. Laine, V. Vhnissi, H. Savin, F. Z. Bouamama, and D. Bouhafs, Phys Status Solidi A **216**, 1900253 (2019).
- <sup>8</sup>J. Lagowski, P. Edelman, A. M. Kontkiewicz, O. Milic, W. Henley, M. Dexter, L. Jastrzebski, and A. M. Hoff, Applied Physics Letters **63**, 3043 (1993).
- <sup>9</sup>S. S. Ostapenko, L. Jastrzebski, and B. Sopori, Semicond. Sci. Technol. **10**, 1494 (1995).
- <sup>10</sup>S. S. Ostapenko, L. Jastrzebski, J. Lagowski, and B. Sopori, Appl. Phys. Lett. **65**, 1555 (1994).
- <sup>11</sup>S. S. Ostapenko and R. E. Bell, J. Appl. Phys. **77**, 5458 (1995).