Review Report for a Ph.D. Thesis submitted to St. Petersburg State University

Title: Enhanced charge carrier thermoemission from the dislocation-related electronic states in silicon

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Dislocations in semiconductors are widely distributed extended defects which electronic states can be disposed in a semiconductor band gap affecting in such a way on the electrical properties of material. Investigations in the field of electronic and atomic structures of dislocations are of a great practical importance for both Si-photovoltaic and Si-photonic industry branches. Recently developed Si wafer direct bonding technique allows to produce the regular dislocation networks (DN) with well-controlled geometry and structural parameters. Such kind of DNs serves as a perfect model object for getting the new information on the fundamental properties of dislocations and grain boundaries in Si, and also may find an application as the active elements in the new generation of microelectronic devices.

Submitted thesis of Maxim Trushin presents the results of theoretical and experimental investigations of the carrier thermoemission from the dislocation-related traps process in silicon. Manuscript consists of four chapters including the introduction, two chapters describing the original theoretical and experimental results and the conclusion chapter summarizing the main results of the work.

The first chapter (introduction) reviewed the existing theoretical models of the electronic properties of dislocations in silicon and their drawbacks which give the motivation for current investigations, namely the developing a new theoretical model describing the influences of dislocation deformation potential, own dislocation local charge and potential of the external electric field on the carrier thermoemission from the core states of dislocations in Si. Also, this chapter contains the short description of Si wafer bonding technique.

Details of theoretical calculations are presented and discussed in chapter two. Author has performed for the first time the exact calculations of the lowering of the potential barrier for electrons and holes thermoemission towards the conduction and valence bands of Si, respectively. It was found this barrier lowering arises due to a superposition of the attractive part of dislocation deformation potential and the potential of outer electric field, which was called by the author as dislocation-related Poole-Frenkel effect. It was shown that the Poole-Frenkel coefficient values noticeably exceed the one corresponding to the Coulomb potential and depend on dislocations type, orientation of the Burgers vector relative to the electric field and on the distances between the neighboring dislocations. It was also shown that extension of the theoretical model to take into account the electrostatic field of charged dislocation line results in additional barrier lowering with the increase of the number of captured carriers but simultaneously leads to the decrease of the corresponding values of the Poole-Frenkel coefficients.

Chapter 3 describes the results of experimental verifications of the developed models which were performed by various junction spectroscopy methods (deep level transient spectroscopy DLTS, isothermal DLTS, capacitance-voltage CV and current-voltage IV characterization) on the n- and p-type bonded samples. In order to study the influence of electric field on the emission processes the bonded samples of n- and p-type conductivity containing regular DN were used. An advantage of such bonded samples – since DN lies strictly parallel to the sample surface at the depth convenient for DLTS investigations, the electric field could be controlled by applied bias voltage. As a result of investigations, the impact of the electric field on the carrier thermoemission from the shallow dislocation-related states towards the permitted bands of Si that obeyed the Poole-Frenkel law was established. By using the isothermal DLTS method, author has reliably defined the Poole-Frenkel coefficient values for the samples with different DN microstructure and found a good agreement with the theoretically predicted values for 60° dislocations. Applying ER-DLTS method, author has revealed the decrease of the activation energy for carrier thermoemission from the shallow dislocation-related states with increase of the number of captured electrons. This effect was explained in the framework of the developed model suggesting that the broadening of the DLTS peak towards the lower temperatures and its shift towards the lower temperatures with increase of occupation rate is caused by the potential barrier lowering with the increase of dislocation-related states occupancy degree.

Final chapter 4 summarizes the main conclusions of the work. The bibliography contains 54 titles, books, papers and presentation in conferences proceedings. The most important results described in the thesis are the discovery of the effects of the reduction of thermoemission barrier both with increase of the charged carrier trap occupancy and in external electric field which may serve as a fingerprint of electronic states located in a close vicinity from dislocation cores.

As a conclusion of my review I may kindly confirm that Ph.D. thesis written and submitted by Maxim Trushin can be accepted and doctoral degree can be awarded to the author after the successful defense.

Below are a few questions to the candidate arose during the reading the manuscript:

1. In Indroduction, page 12, it was claimed that the shallow traps energy position in Si band gap is around 70-90 meV, whereas experimentally defined value for STn traps is around 150 meV. How this difference can be explained? What criteria of distinction between the shallow and deep levels did you use?

2. Does it necessary when considering thermoemission enhancement to account also for the possible variation of the defect level position inside the Si band gap relative to the unperturbed permitted band? It seems that the deformation potential of dislocation together with the electrical field can significantly shifts the energy position, static and dynamic characteristics of the levels under consideration.

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