

Evaluation of the PhD thesis

**“Enhanced charge carrier thermoemission
from the dislocation-related electronic states in silicon”**

submitted by

Maxim Trushin

Saint Petersburg State University, May 2014

In semiconductor technology dislocations are mainly considered as defects that should be avoided due to their detrimental action on the device performance. However, it is often ignored that dislocations in silicon/semiconductors form native nanostructures exhibiting exceptional properties with beneficial action. Moreover, silicon direct wafer bonding allows formation of well-controlled dislocation networks (DNW) with a geometry and structure depending on the misorientation (tilt, twist) between the bonded wafers. Accordingly, concepts for novel devices such as IR light emitters making use of the dislocation-related luminescence, FETs with DNW in their channel making use of the enhanced (supermetallic) carrier transport at the dislocations or even Si-based thermo electric generators with $ZT > 1$ caused by DNW are under evaluation. Despite the long term study of dislocations in silicon/semiconductors there are still many open questions, especially regarding their electrical and luminescence features. Usage of DNW as ‘model dislocations’ helps to find missing answers needed to optimize novel devices with dislocations as active component.

The thesis of Maxim Trushin contains novel scientific results delivering an important contribution to open questions. It describes the analysis of enhanced carrier emission from electronic states in the band-gap of silicon caused by the dislocations. The work was done by the candidate in a very systematic manner. This is also reflected by his thesis itself which is clearly written and very well organized. All figures are of very good quality and support the understanding. The bibliography (pages 44-45) contains the most important papers related the topics of the thesis. The thesis is divided in four main chapters.

Chapter 1 gives an **introduction** to the thesis including motivation of the work, previous and related studies and description of the main properties of dislocation networks.

In **theoretical part**, i.e. in chapter 2, calculations are given that describe for the first time the influence of the dislocation deformation potential on the carrier thermo-emission from the states of screw and 60° dislocations towards the conduction and valence band of Si. The following important points were taken into consideration: (i) The interaction of the dislocation deformation potential with an external electric field was analyzed, yielding in a barrier lowering for carrier thermo-emission which was shown to be very similar to the Poole-Frenkel effect. (ii) The Poole-Frenkel coefficients were calculated, taking into account the dislocation type, the orientation of the Burgers vector relative to the electric field and the distances between dislocations. (iii) The influence of the own electric field of charged dislocation lines on the Poole-Frenkel coefficients was analyzed.

The **experimental results** are described in chapter 3. Sample sets of p-type and n-type silicon containing DNW with screw and 60° dislocations lying parallel to the surface were studied. The samples used, were prepared in a sophisticated industrial environment at SOITEC (France), i.e. under nearly ideal conditions. The distance to the surface was chosen to be small so that the DNW was located within the space charge region of Schottky contacts prepared on top. For the experimental investigation techniques of junction spectroscopy and characterization were used, namely deep-level transient spectroscopy (DLTS) including isothermal DLTS, capacitance-voltage (CV) and current-voltage (IV) characterization. Moreover, results of structural analysis of the DW by transmission electron microscopy were taken into account.

DLTS revealed the presence of deep and shallow traps in the upper and lower part of the band-gap of Si, originated by the DNW. The deep states were interpreted to be caused by point defects and defect clusters in the vicinity of the DNW. The shallow traps were attributed to deformation-induced 1D dislocation band-like states. Donor-like / acceptor-like behavior was found for the dislocation levels in the lower / upper half of the band-gap, respectively. The impact of external electric field on the carrier thermo-emission from the shallow states was investigated. It was found to follow the Poole-Frenkel law. The experimentally determined values of the coefficients are in good agreement with the calculated data.

More details of the comparison between experimental observations and theoretic calculations are presented in a condensed manner in the **conclusions** (chapter 4) of the thesis.

The scientific success of the work of Maxim Trushin is reflected by his publications about the topics of his thesis (see PI-PIV) and his contributions to six international scientific conferences (see § 1.6 on page 15). Moreover, his scientific visibility is documented by 17 other publications since 2005, where he is the first author for 8 papers.

I am impressed by the very good quality of the thesis of Maxim Trushin and evaluate it with the grade '**very good**'.

Cottbus, May 27, 2014

Prof. Dr.sc.nat. Martin Kittler
(Director Joint Lab IHP/BTU)

After revision of the thesis I have one minor technical remark: The word Poole-Frenkel effect is not written consistently in the right manner. Quite often Pool is written **without 'e'** at the end. The missing 'e' should be corrected.

Questions to the candidate

Q1

It is known that charge carriers are transported along the dislocation network in Si.

Do you expect that this transport effect may have an influence during DLTS filling pulses?

Maybe the transport effect dilutes the occupation of states?

Will the area of the Schottky contact have an influence?

Q2

In the thesis you said that deep levels observed by DLTS (in your nearly ideal sample sets) are caused by point defects or defect clusters such as interstitials or oxygen related defects.

Why do you exclude the action of metallic impurities?

Would it be possible to passivate such defects (?) or to remove them by appropriate thermal treatment?

Q3

A more general question:

Do you expect a Poole-Frenkel-like behavior for dislocations in other semiconductors, too?

If yes, what is the parameter of the material with the strongest influence?